Department of Civil Engineering

REMOTE SENSING AND GIS TECHNIQUES FOR MONITORING AND PREDICTING LAND DEGRADATION AND IMPACTS OF ENGINEERING SOLUTIONS IN AN AREA

Muhammad Junaid Siddiqi

"This thesis is presented for the award of the Degree of Philosophy of the Curtin University of Technology"

June 2009

ABSTRACT

Salinity, waterlogging and drought are major causes of land degradation and serious threats to sustainable agricultural productivity in the south-west agricultural region of Western Australia (WA). The spectral signatures of pasture plants under drought, waterlogging and nutrient deficiency were examined in a greenhouse study using both a field and an analytical laboratory spectrometer (400 to 2,500 nm wavelength).

Drought stress group (RWC, 39.9%) has the highest reflectance of 48.2%, waterlogging group (RWC, 49.7%) with a magnitude of 43.1% reflectance and control group (RWC, 61.5%) has the lowest of 41.9%. The highest separability based on magnitude among control, waterlogging and drought stress groups is located at reflection band at 1,666 nm, 1,818 nm and 2,216 nm and at 1,450 nm absorption bands. Remote sensing and GIS techniques were used to predict risks of soil salinity and waterlogging in the study area. Time-sequenced Landsat TM satellite data and groundwater data were analysed to delineate areas where major changes in soil salinity, waterlogging have taken place before and after engineering interventions of deep drains.

The rainfall data analysis of all cities in the south-west of Western Australia indicate that annual rainfall has been decreasing since 1969 for some cities in the region and rainfall is decreasing in some cities since 1975. The winter season rainfall shows a downward trend and summer season rainfall shows an upward trend linked to an increase in the frequency of summer storm events in the south-west, in the Wheatbelt and in the east of Western Australia. The annual rainfall and summer season rainfalls have been increasing in the north of Western Australia and both annual rainfall and summer season rainfalls show an increasing trend. Climate change was studied for northern, eastern, Wheatbelt and south-west of WA and its impacts of on surface runoff, groundwater recharge, and land degradation were studied.

Deep open drains were monitored in the two major drainage districts of Narembeen and Dumbleyung in Wheatbelt of Western Australia. The efficacy of drains in mitigating the problems of waterlogging and salinity in the area was studied. Information on monitoring of drains in six coastal districts in Western Australia, from Australia and other countries was collated and a coastal drainage best management practices ‘BMP Toolbox’ has been developed.

ACKNOWLEDGEMENTS

I would like to thank my Ph.D. supervisor Prof. Hamid Nikraz from the bottom of my heart for his guidance, encouragement and support throughout the study period. Special thanks are due to Dr. Azam Khan who was a lecturer at Civil Engineering Department, Curtin University of Technology before and now he is working at State Water, Sydney, NSW. He helped me to get an Australian Postgraduate Award for this study and provided me guidance and support during the study. I wish to thank Dr. Waqar Ahmad and Dr. Riasat Ali of CSIRO, Perth for their help during the course of study. I also wish to thank CSIRO Land and Water, Perth for providing satellite imageries for the study. My friend Mr Shahram Sharafi, Hydrogeologist helped me to set up ArcView GIS extensions for flow accumulations. His help and guidance to complete this thesis is greatly acknowledged.

I am indebted to CSIRO Livestock Industry for their top-up scholarship and greenhouse and lab facilities for the study.

I wish to thank URS, Perth, Australia for providing me an opportunity to work for them. During my work at URS, I worked for different clients and have used their data and literature for some case studies presented in this thesis.

I am grateful to my wife and four children who understood the need for this study, compromised with the situation and provided me all the moral support for the study. I dedicate my thesis to my wife Farah, and four children Hiba, Maha, Ahmad and Zoha.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

OBJECTIVES OF THE Ph.D. STUDY

The objectives of this research work were:

a) To detect drought, waterlogging and micronutrient stress on pastures using spectroradiometers in a greenhouse study.

b) Evaluation of remote sensing and GIS techniques to predict the impacts of drought, waterlogging and salinity on crops in the Wheatbelt of Western Australia and to delineate areas where major changes in soil salinity, waterlogging have taken place before and after engineering interventions of deep drains using time-sequenced satellite imageries.

c) Evaluation of remote sensing and GIS based tools to identify and map soil salinity and waterlogging in a sub-catchment and to predict land degradation in catchments of the Wheatbelt.

d) Analyse the groundwater monitoring data of deep drainage sites in the Wheatbelt of Western Australia using GIS.

e) To develop Flow Accumulation techniques to delineate natural drains in the Wheatbelt of Western Australia and to quantify parameters in a catchment to study land degradation.

f) Study climate change in Western Australia and its effects on surface and groundwater flows, floods and episodic rainfall events in different parts of Western Australia.

g) Develop a BMP Toolbox to compile research data and information about methods and techniques for choosing best available methods to develop surface and deep drainage in inland and coastal areas.

INTRODUCTION OF THESIS

The research undertaken to achieve the objectives of the Ph.D. study are detailed in the following six chapters. All of the chapters of this thesis begin with an introduction, then the relevant literature review is given in each chapter, research methodology, analyses of data and conclusions are given at the end of each chapter.

Chapter 1 explains the methodology and analyses of results of a glasshouse study conducted from October, 2003 to March, 2004 to determine the separability of the spectral signatures of plants under drought, waterlogging and micronutrient stresses in a greenhouse using spectrometers. Jackson and Ezra (1985) measured spectral responses in eight wavebands by taking several readings of a radiometer over several rows of cotton after dessication was induced to stems. The reflectance and emittance of dessicated plants were compared with a control row. Penuelas (1992) developed a Water Index (WI = R970/R900) to indicate water status after studying the reflectance in the 950–970 nm region. The WI was also used to estimate the plant water concentration (PWC) by ground-based reflectance measurements (Penuelas *et al*., 1997). Tian (2001) measured wheat leaf spectra using a FieldSpec-FR radiometer to spectrally identify and characterize the water deficiency symptoms. The spectral signatures of pasture plants under drought, waterlogging and nutrient deficiency were examined in a greenhouse study using both a field and an analytical laboratory spectrometer (400 to 2,500 nm wavelength).

Drought stress group (RWC, 39.9%) has the highest reflectance of 48.2%, waterlogging group (RWC, 49.7%) with a magnitude of 43.1% reflectance and control group (RWC, 61.5%) has the lowest of 41.9%. The highest separability based on magnitude among control, waterlogging and drought stress groups is located at reflection band at 1,666 nm, 1,818 nm and 2,216 nm and at 1,450 nm absorption bands. The spectral signatures for drought, waterlogging and micronutrients stress computed during Ph.D. study may be used to indentify drought, waterlogged and nutrient stressed plants in a controlled environment.

Chapter 2 presents remote sensing and GIS techniques to monitor the efficacy of deep drains in controlling salinity and waterlogging in an area. Groundwater pumping and deep open groundwater drains are used to reduce land salinisation at scales from managing local discharges to regional systems (Otto and Salama, 1994; Ali and Coles, 2001). George (1991) recorded radial effects of greater than 100 m in deep open and tile drains in yellow earth on hill slopes in the eastern Wheatbelt. Speed and Simons (1992) reported radial effect of 10 m of shallow open drains (<1.5—1.8 m) in heavy textured, dispersive, and low permeability soils with little effect on watertables.

The long-term groundwater and climatic data were analysed to find the interactions of groundwater table fluctuations with episodic rainfall events. The highest groundwater contours before the construction of deep drains were observed in 2002 at Beynon Road in Dumbleyung. Lowest groundwater contours were in 2003. On an average groundwater level in all observation bores in 2002 was at 281.8 m AHD which declined to an average of 280.5 m AHD in 2003 with an average drawdown of 1.2 m in groundwater level. Highest groundwater levels observed in 2003 after winter rainfall recharge at Beynon Road in Dumbleyung resulted in groundwater level recovery of 0.6 m. The lowest groundwater level was observed in 2004 with an average groundwater level of 280.3 m AHD with an average recovery of 0.5 m. Groundwater level rose in 2005 after recharge from rainfall infiltration. During 2005, the average groundwater level rose to 281.2 m AHD. The maximum drawdown of 1.7 m and a minimum drawdown of 1.3 m occurred in monitoring bores from DD1 to DD4 in the north-east corner close to collector drain and in monitoring bores from DD25 to DD31 in between lateral drains where perched groundwater is visible in the satellite imagery.

Chapter 3 presents remote sensing techniques to identify and map saline, waterlogged and drought area in the two drainage districts of WA. Metternicht and Zinck (1996) used a synergistic approach to map salt and sodium affected surfaces, combining digital image classification with field observation of soil degradation features and laboratory determinations. Metternicht and Zinck (2003) provided a review on satellite imagery covering the visible to infrared regions of the spectrum for identification and mapping of saline areas. The reflectance increases with increasing quantity of salts on the soil surface. Salt-affected soils show relatively higher spectral response in the visible and near-infrared regions of the spectrum than non-saline soils do, and strongly saline-sodic soils present higher spectral response than moderately saline-sodic soils (Rao *et al.*, 1995). The Land Monitor Project, a project of the WA Australian Salinity Action Plan supported by the Natural Heritage Trust, has mapped areas of shallow watertable and salinity risk and reports of fifteen districts in Wheatbelt. Caccetta (1997) cautioned for the interpretation of the prediction results as to a large degree, predictions relied heavily on the landform variables derived from the DEM and therefore are partially bound by the errors in landform partitioning.

Time-sequenced Landsat TM satellite data and groundwater data were analysed to delineate areas where major changes in soil salinity, waterlogging and land degradation have taken place before and after engineering interventions of deep drains. High resolution satellite imageries were analysed using different indices and unsupervised classification to identify soil salinity, waterlogging and drought areas in WA.

In Chapter 4 explains the procedure of using GIS and DEM to delineate catchment boundaries, surface slopes and identify salinity risk in a catchment. A DEM is prepared from contour data or stereo-satellite data using geographical information system (GIS). Classification of the catchments to different hydrogeomorphic units can be performed using GIS techniques (Salama *al et*., 1996; 1997b; 1999a). A high-quality DEM produced by Land Monitor that can be used to delineate stream network lines, drainage lines and hydrogeomorphic parameters required for the characterisation of the area. Most of the salinity of soil is associated with shallow water levels in the lower areas of the catchment and salinity decrease with increase in water level depth with increasing altitude. In the confined aquifers there is an inverse relationship between water level and aquifer depth (Salama *et al*., 1996; 1997b; 1999a). Caccetta (1997) processed DEM data with GRASS routine r.watershed and found water accumulation algorithm produced drainage network that was within 600 m of the true drainage network. Chow *et al*., (1988) defined hydrological process of surface water flow as when the soil moisture capacity is exceeded; the excess rainfall becomes overland flow until it is drained in one of the catchment channels.

Flow Accumulation technique was used to find the creeks, streams and drainage lines in an area using GIS and DEM and the results were verified from orthophotos of the area. Use of GIS was made in monitoring pollutants in Torbay Catchment. The methodologies for digitising drains or streams from topographic maps and aerial photographs have been developed in Albany, Denmark and Mount Barker area. GIS methodology was explained to get statistics on number of streams and drains of different orders and total lengths of streams and drains. A graduated symbol classification using GIS was used to display a range of values of Reactive Iron, NH_4 Phosphorus in soil samples taken from Torbay catchment. The areas of Phosphorus pollution from surface runoff and Nitrogen leaching in groundwater and making its way to Torbay streams and drains can be identified from these maps.

In Chapter 5, the impacts of climate change on groundwater recharge, surface runoff and land degradation in Western Australia were studied. CSIRO (2001) has projected changes in Australian annual rainfall in 2030 and 2070 for Western Australia. There is a likelihood that a lower annual average rainfall in the south-west of Western Australia will occur and this decrease in annual rainfall will be -20 to +5% of average rainfall by 2030 and -60 to +10% of average rainfall by 2070. Northern and eastern parts of Western Australia will experience decrease in annual rainfall of -20 to +10% by 2030 and -60 to +40% by 2070. The central eastern desert area of Western Australia will have a decrease in annual rainfall of -12 to +12% by 2030 and -36 to +36% by 2070. Extreme events such as flooding and droughts are projected to increase in frequency and severity as the global climate changes (ABARE, 2007).

The mapping of highest daily rainfall amounts and maximum daily rainfall isohyets or contours for Western Australia was done using GIS to delineate areas of risk of flooding and land degradation. A study was conducted to test the hypothesis that the average intensity of tropical cyclones has increased and to determine surface runoff flow rates associated with specified rainfall events of specific annual recurrence interval. The Time-Area method, Initial Loss-Continuous method and the Rational Method were used to determine the peak flow rates and volume of surface water runoff and the results were compared with each other. This analysis showed that an IL-CL model can be used to calculate surface runoff at Cleo pit with rainfall intensity data. Impacts of climate change on groundwater recharge and surface runoff were simulated using AgET model for Buntine-Marchagee catchment. The rainfall data analyses of all cities in the south-west of Western Australia indicate that annual rainfall has been decreasing since 1969. The winter season rainfall shows a downward trend and summer season rainfall shows an upward trend linked to an increase in the frequency of summer storm events in the south-west, in the Wheatbelt and in the east of Western Australia. The annual rainfall and summer season rainfalls have been increasing in the north of Western Australia

In Chapter 6, information on best management practices (BMPs) from Australia and other countries on coastal and inland drainage were collated in a database and a 'BMP Toolbox' was developed. Diffuse sources of N largely originate from rural practices including fertilised arable lands, pasture, orchards and intensive horticulture practices where fertiliser application is excessive and groundwater levels are high (Gerritse, 1992; Lantzke, 1999). In urban areas, appreciable quantities of fertilisers are applied to parks, gardens and sports grounds. It has been estimated that fertilisers applied to urban gardens account for approximately 10% of total nutrient inputs to the Swan–Canning Estuary (SCCP, 1999). The low concentrations suggest groundwater is not a major pathway for N to tributaries from the Darling Plateau (Turner *et al*., 1991). Much of the N research in Australia has focused on estuarine environments rather than freshwater (Hart and Grace, 2000). Recent research suggests that N plays an important role, for example, in riparian zones (Rassam *et al*., 2003), irrigation (Mundy *et al*., 2003) and surface and groundwater (Davis and Koop, 2001; Hunter, 2000).

The prospect of increasing volumes of effluent produced by deep drains has increased concerns about the acidic, trace element rich waters that can be produced by such drainage systems and the impacts of these on receiving environments (Dogramaci and Degens, 2003). Initial investigations of some major drainage schemes have found that these can discharge waters of pH 2-3 with a salinity of 30,000 to 50,000 mg L^{-1} at 5-10 ML per day (Ali *et al*., 2004b). There are no reports of investigations to characterise the geochemical risks associated with these drainage waters, though limited studies indicate that the waters can contain elevated Al, Mn, Co, Ni and Pb (Ali *et al*., 2004b; Tapley *et al*., 2004). Shallow acidic groundwater likely to be intercepted by the drains can contain significant concentrations of Al, Cu, Fe Mn, Pb and Si (Mann, 1983; Lee and Gilkes, 2005).

All the research on drainage and monitoring results are given in chapter 6. BMPs to reduce nutrient export to the catchment and the techniques, such as riparian buffers, irrigation management, effluent management, infiltration basins, retention basins, detention basins, spoil management and in-stream structure are explained.

The first five chapters of this thesis are about the problem finding and the sixth chapter is about solutions of the problems.

1 SPECTRAL SIGNATURES STUDY FOR DROUGHTS, WATERLOGGING AND MICRONUTRIENTS

1. 1 Introduction

Crop and pasture growth is affected by droughts, waterlogging and nutrients deficiency in Western Australia (WA). Farmers in WA experienced severe droughts in 1969, 1987 and 2002 that resulted in the low yields of crops and pastures, low water levels in the farm dams and tanks, and non availability of feed for animals. The Australian government has estimated that a nationwide drought in 2002 caused widespread land degradation and resulted in 12.5% reduction in farm output and farmers' income was reduced by 5 billion dollars.

In WA, 1.8 M ha are affected by salinity at present, and this could double within 20 years, and double again before equilibrium is reached; over half the State's divertible water is already saline, brackish or of marginal quality. There is waterlogging in one million hectares of crops and 0.5 million hectares of pastures in wet seasons to half of these areas in drier years in Western Australia. These conditions affect the growth and development of the root system of the plants and can lead to severe yield losses. The National Land and Water Resources Audit has identified that 4.3 million hectares (16%) of the south-west region have a high potential of developing salinity from shallow watertables and up to 8.8 million ha (33%) in Western Australia could be at high risk of developing shallow saline water tables by the year 2050 (http://audit.ea.gov.au/).

1. 2 Drought Stress

The remote sensing techniques of studying reflectance and emmitance using a radiometer canopy geometry changes were apparently greater than those caused by leaf physiological and anatomical changes were used to study water status in vegetation by Jackson and Ezra (1985). They measured spectral responses in eight wavebands (three visible, two near-IR, two mid-IR, and one thermal IR) by taking several readings of a radiometer over several rows of cotton (Gossypium hirsutum L.). The stems of one row were cut above the soil after an initial measurement to induce dessication. The reflectance and emittance of dessicated plants were compared with a control row. The visible and thermal IR showed a larger change than the near-IR to show water stress. Canopy geometry was a major factor in showing changes in reflectance than those caused by leaf physiological and anatomical changes in all but the visible red band. Bowman (1989) reported the potential of measuring plant water stress by using leaf reflectance.

The thermal radiation emittance of the canopy can be used to assess water stress (Penuelas *et al*. 1992). The plant water status is also depended on spectral absorption features by water in the 400–2500 nm region. Several researchers in the past have used leaf and crop reflectance for measuring water stress Penuelas *et al*. (1992), Penuelas *et al*. (1993), Penuelas *et al*. (1994), Penuelas and Filella and Sweeano (1996).

Penuelas (1992) developed a Water Index (WI = R970/R900) to indicate water status after studying the reflectance in the 950–970 nm region. The results showed that the ratio of the reflectance at 970 nm which is one of the water absorption bands to the reflectance at 900 nm as reference wavelength was able identify the changes in relative water content (RWC), leaf water potential, stomatal conductance, and cell wall elasticity. The WI was also used to estimate the plant water concentration (PWC) by ground-based reflectance measurements (Penuelas *et al*., 1997). The WI was significantly correlated with PWC when all the species were considered together or individually in extreme dessication of experimental plants. Their correlations increased when WI was normalised by NDVI. They observed that wavelength of the trough corresponding to water absorption band tended to shift from 970-980 nm to lower wavelengths 930-950 nm with decreasing PWCs. Their conclusion was that a simple radiometer measurement of plant reflectance at 680, 900, and 970 nm could be useed to speed up the measurement of PWC for wildfire risk evaluation and drought assessment.

Allen and Richardson (1968) observed that reflectance spectra of green vegetation beyond 1300 nm were strongly influenced by liquid water absorption. The other spectral indices to estimate plant water content used water absorption bands at 1,200, 1,450, and 1,780 nm (Gao, 1996; Shibayama *et al*., 1993). Matson (1994) correlated AVIRIS data from 1,600 nm to 1,800 nm to nitrogen concentration estimates and found that 64% of the variance was associated with the water absorption rather than nitrogen. They suggested that any remote sensing algorithm must consider the influence of leaf water.

Tian (2001) measured wheat leaf spectra using a FieldSpec-FR radiometer to spectrally identify and characterize the water deficiency symptoms. A spectral analysis was used to normalise the spectral absorption parameters using wavelength position (nm), depth and area (relative value) from each wheat leaf spectrum. The relative water content (RWC) was measured for each wheat leaf sample. The linear regression between the spectral absorption feature parameters and corresponding RWCs of 110 samples indicated that reflectance spectra of wheat leaves in the 1,650-1,850 nm regions were dominated by water content. The 1,650-1,850 nm spectral absorption became clear with a decrease in wheat leaf RWC.

1. 3 **Micronutrient Stress**

Soils of WA are deficient of both macro and micronutrients. The macronutrients required for the proper growth of forage crops are phosphorus, potassium, sulphur, magnesium, and calcium. The micronutrients include: iron, manganese, boron, zinc, copper, and molybdenum. Nitrogen is one of the most important elements that induce vigour in plants. Quality pastures contain a high percentage of total digestible nutrients and have a high percentage of protein.

Hyperspectral remote sensing offers the potential to detect and map both macro- and micro-variations in pasture quality due to its use of narrow spectral channels of less than 10 nm. These narrow spectral channels allow the detection of detailed features, which could otherwise be masked by broadband satellites such as Landsat TM or Aster (Schmidt and Skidmore 2001).

Nitrogen status of various crops has been related to reflectance in the visible and near-infrared (NIR). Leaves with higher nitrogen content have stronger spectral reflectance in certain blue and NIR wavebands. Under limiting nitrogen levels, plants reflect more in the red spectral region due to lower chlorophyll content and reflect less in NIR region. Various reflectance ratios and indices have been used to detect nitrogen deficiencies in plants. Recent work by Taylor *et al*., (1998) has demonstrated that spectral measurements in the red (671±6 nm), green (570±6 nm) and NIR (780±6 nm) could be used to estimate forage yield and N removal by bermudagrass (Cynodon dacrylon L.). Shortwave infrared data from an Airborne Visible/Infrared Imaging Spectrometer (AVRIS) was used to estimate forest canopy nitrogen and lignin content (Martin and Aber, (1997).

Adams *et al*., (2000) related micronutrient deficiencies in soybean (Glycine max L.) to reflectance and fluorescence measurements at 550, 650 and 750 nm in a laboratory. Canopy reflectance can also be used to discriminate differences in foliar nitrogen concentration. This implies that the same species can reflect differently depending on environmental factors such as nutrient levels. This offers the possibility to map variation in pasture quality using high-resolution sensors. To determine spectral signatures and determine if they can be separated of pastures plants under water stress and micronutrient stress in a greenhouse using a spectroradiometer and use these spectral signatures to identify these stresses in the field using high resolution satellite imageries.

The objectives of this greenhouse study are to determine the separability of the spectral signatures of two pasture plants under water stress, waterlogging stress and micronutrient stress in a greenhouse using a laboratory spectrometer and a field spectrometer and use spectral signatures obtained from this study to identify water stress, waterlogging stress and micronutrient stress in the field using high resolution satellite imageries.

1. 4 **Materials and Methods**

1.4.1 Preparation of plant samples

Different plant materials and the same material in different condition reflect and absorb differently at different wavelengths. The reflectance spectrum of vegetation is a plot of the fraction of radiation reflected as a function of the incident wavelength and serves as a unique signature for the vegetation. In principle, a plant material can be identified from its spectral reflectance signature if the sensing system has sufficient spectral resolution to distinguish its spectrum from those of other materials. An effort was made to study changes in spectral signatures of annual pasture species under drought and waterlogging from control and micronutrient stress on annual ryegrass and subclover from control.

1.4.2 Drought Stress Group

Annual ryegrass (*Lolium rigidum* var. “Wimmera”) was planted in Wongan loam soil in 45 pots on 20 October 2003 in a glasshouse at CSIRO, Floreat, Perth, WA. The 45 pots were randomly divided into three groups, drought stress, waterlogging (pots in water filled containers) and the third group was used as control. The annual ryegrass was grown in plastic pots (diameter 16 cm and height 42 cm) with holes at the bottom for drainage. Fifteen pots of each group were put on wheeled benches and the positions of the benches in the greenhouse were changed fortnightly for providing constant temperature and sunshine to plants. The meshed-cloth shade on the roof of the greenhouse was pulled down on 8 November 2003.

1.4.3 Treatment of Plants

The daily potential evapotranspiration from subclover and annual ryegrass pots were estimated from 28 November 2003 to 2 December 2003. Five pots of annual ryegrass and subclover were weighed after leeching of water was stopped after daily watering and difference in weights of pots were recorded next day before watering. The daily potential evapotranspiration for annual ryegrass was estimated 500 mL day^{-1} and for subclover 300 mL day^{-1}. The daily potential evapotranspiration was used to calculate daily watering of the annual ryegrass and subclover.

1.4.4 Control Group

The 15 pots of annual ryegrass grown in Wongan loam soil were used as control and 500 mL day^{-1} water was supplied to all pots. All the seeding annual ryegrass plants were trimmed from top and kept at 30 cm height to stop senescence of the plants. The greenhouse location at CSIRO, Perth and drought stress of annual rye grass on different dates are shown in plates from 1-1 to 1-7.

Plate 1-1: Greenhouse location at CSIRO, Perth

Plate 1-2: Greenhouse Study setup at CSIRO, Perth

Plate 1-3: Annual Rye Grass in sand on 22/10/03

Plate 1-4: Annual Rye Grass in soil on 10/11/03

Plate 1-5: Annual Rye Grass in soil on 3/12/03

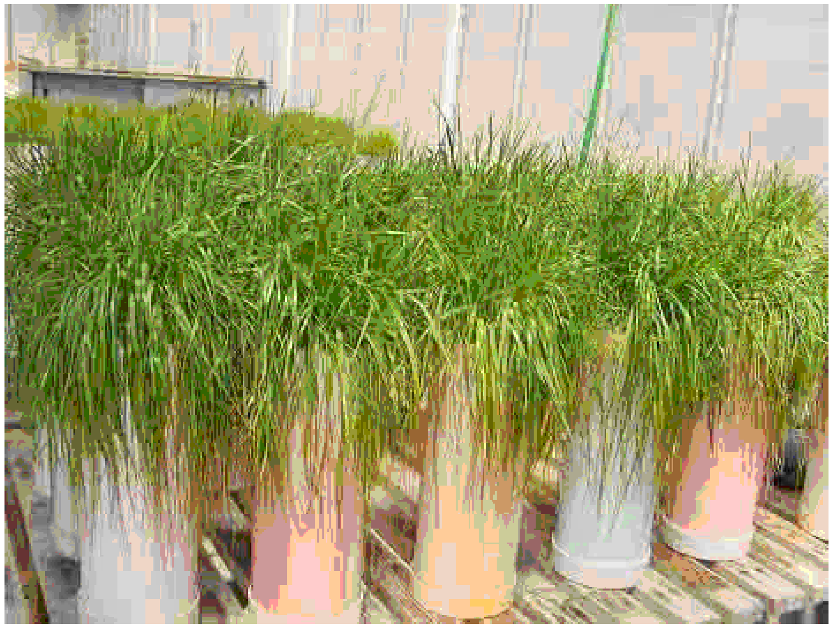


Plate 1-6: Annual Rye Grass control group

1.4.5 Drought Stress Group

To induce drought of 15 pots of annual ryegrass were watered 300 mL day^{-1} since 21 December, 2003. Five pots of water stress group were given extra water stress, daily watering of 275 mL day^{-1} was reduced to 200 mL day^{-1}, from 18 February 2004 to 21 February 2004. Daily watering was gradually reduced to 100 mL day^{-1} until 26 February 2004. A dry spell was induced to the five pots from 28 February 2004 to 4 March 2004 and final readings were taken 5 March 2004.

1.4.6 Waterlogging Stress Group

To 15 pots of annual ryegrass, waterlogging was induced on 17 December 2003 by placing the pots in containers filled with water 35 cm deep (Plate 1-8). The plants were watered daily and water was topped up in the containers that kept the soil moist all the time. The roots of the annual ryegrass started coming out of the soil at the top of the pots and there were no visible symptoms of waterlogging stress on plants. At that point, it was decided to completely submerge few pots in water to see the stress of waterlogging on plants.

Plate 1-7: Annual Rye Grass drought group

Plate 1-8: Annual Rye Grass waterlogging group

On 5 January 2004, two pots were put in 45 liters bins filled with water and completely submerging the pots to see the effect of waterlogging on plants. These plants also survived well in water and roots started to float in water. Two more plants were put in bins on 12 January 2004 to make a replication of waterlogging treatment (Plate 1-9). All the plants in waterlogged condition were growing well and flowering but some leaves started turning yellow at the final stages of the experiment after 1st March 2004.

Plate 1-9: Annual Rye Grass waterlogging in bins group

1.4.7 Micronutrient Stress Study

In order to study micronutrients stress, subterranean clover (*Trifolium subterraneum* var. “Dalkeith”) was planted in 30 pots (diameter 16 cm and height 35 cm) and annual ryegrass was planted in 30 pots (diameter 16 cm and height 42 cm) on 20 October 2003 in nutrient deficient washed white sand. The sand was tested and it contained nitrogen and phosphorus 2 mg kg^{-1} and potassium 13 mg kg^{-1} (Appendix- 2).

Annual ryegrass was grown in two groups of fifteen pots and the positions of pots were re-randomised fortnightly on the benches for providing constant temperature and sunshine to plants. Similarly, subclover was grown in two groups of fifteen pots and the positions of the pots in the greenhouse were re-randomised fortnightly for providing constant temperature and sunshine to plants.

1.4.8 Micronutrient Stress Group

All pots of the experiment were watered every day. In the beginning for fertilisation, Thrive solution was prepared by mixing 16 grams of Thrive granules with nine litres of water and applied to all pots after seeding. The germination of the subclover and annual ryegrass started on 24 October 2003 and was completed on 27 October 2003. The germination of the annual ryegrass was completed on 28 October 2003 but the germination of the subclover was patchy. Thrive fertiliser was applied to all pots by mixing 16 grams of Thrive granules with 9 litres water on 1 November 2003. All the germinated subclover plants in 30 pots were removed and pots were topped-up with white sand and the subclover seeds were re-sown on 4 November 2003. The cooler in the greenhouse started working on 4 November 2003. The new schedule was set to water the plants sown in sand twice daily. The germination of the subclover in white sand was completed on 8 November 2003. Thrive fertiliser was applied weekly to plants until 3 December 2003 and then watered the plants without any fertiliser to leach the macro and micronutrients before the application of laboratory prepared fertilisers.

Two stock solutions were prepared on 19 December 2003, 1st with all macro and micronutrients and 2nd as 1st but without copper, zinc and molybdenum (Appendix 1-1). These solutions were prepared by adding 50 mL of each macro nutrient solution to 50 litres of water and 5 mL of each micronutrient solution to 50 litres of water. Each pot of the experiment was given 300 mL day^{-1} of these solutions twice weekly and for the rest of the days daily watering of 300 mL day^{-1} was applied since 19 December 2003. A fertiliser mix without copper, zinc and molybdenum micronutrients was supplied to 15 pots of subclover and 15 pots of annual ryegrass. The remaining 15 pots of each group were supplied with a fertiliser mix containing the missing micronutrients and these groups were used as control. All the flowering subclover plants were trimmed and kept short to stop senescence of the plants.

1. 5 **Spectrometers Used**

Two spectrometers, Portable Infrared Mineral Analyser (PIMA) and Near Infrared Spectrometer (NIRS), were used to take reflectance and absorbance readings on different dates, respectively. The electromagnetic spectral signatures of pasture plants under drought, waterlogging and micronutrient stress were examined in a greenhouse study using PIMA and NIRS spectrometers. Spectra readings of plants using PIMA and NIRS instruments have been recorded after every 10 days.

1.5.1 PIMA

PIMA (Portable Infrared Mineral Analyser) is a short wave infrared reflectance spectrometer that operates in the wavelength region from 1,300 to 2,500 nm with a spectral resolution of 7-10 nm and a sample interval of 2 nm. In this wavelength region, Peñuelas *et al*., (1997) and Tian *et al*., (2001) found out that the strongest water absorption bands in plants occur in the 1,400 nm and 1,900 nm regions of the spectrum.

The PIMA is used for minerals analyses but it was used for fresh green plants. The PIMA is a short wave infrared reflectance spectrometer that operates in the wavelength region from 1,300 to 2,500 nm. In this wavelength region, minerals that contain hydroxl radicals (such as clays, amphiboles, some sulphates) and carbonate radicals, absorb incident radiation at specific wavelengths and in relative amounts that are diagnostic of the mineral species. Borates, phosphates, vanadates, ammonium minerals and some others also produce diagnostic spectra. The minerals absorb wavelengths of incident radiation according to the energies of the stretching and bending vibrations of the carbonate and hydroxl radicals in the mineral. These energies of vibration depend on the cation to which the radical is bonded (e.g. aluminium, iron and magnesium) and the structure, energies of bonding and degree of ordering of crystal lattice. Geologists use the PIMA to identify fine grained mineral species, and their crystallinity and composition (PIMA manual).

1.5.2 NIRS

The laboratory spectrometer, NIRS (Near Infrared Spectrometer) has absorbance wavelength range from 400 to 2,500 nm with a resolution of 2 nm.

The NIRS is used for dried samples but fresh samples of plants were used. The concentration of inorganic components in forage crops varies according to crop maturity, temperature and soil pH and composition. The percent dry matter composition of forage material is relatively low in mineral concentration. Because of their low concentrations, the absorptions due to the presence of minerals are difficult to detect above the changes in signal due to repack errors of the repetitive sample presentations. Theoretically, there are no absorption bands for mineral species in the infra-red region and specific work to determine mineral content in forage indicates that NIR analysis could be directly measuring organic acid (NIRS manual).

1. 6 **Measurement Methods**

1.6.1 PIMA Spectral Measurements

The first readings of annual ryegrass and subclover were taken by placing sward of leaves from a pot onto PIMA's Field of View (FOV) that was 10 mm by 2 mm in size and covered it by brown cardboard. Four readings were taken by moving pots 45 degrees and placing upside of 10 leaves covering completely instrument FOV. All of the four-reflectance readings were different from each other. It was decided to take next readings by cutting the leaves of the plants and placing it over FOV of PIMA while the instrument is sitting upright on its stand.

The reflectance readings of plants were taken in the glasshouse with PIMA. More than five leaves of plants were cut from a pot and upside of five or more leaves were placed on instrument's FOV to completely cover it before taking readings. It took only 3–5 minutes between spectral measurement using PIMA.

Plate 1-10: PIMA radiometer for spectral measurements

1.6.2 NIRS Spectral Measurements

Laboratory spectrometer (NIRS) measured the absorbance of the plants. Plant leaves were cut from five pots of a group for taking NIRS readings (Plate 1-11). In order to minimize loss of moisture from leaves during transportation to laboratory, leaves were put in plastic bags and all samples of plants were transported to laboratory in an Esky. The annual ryegrass leaves in the cell were facing upside during scanning. Fresh green leaves of annual ryegrass were cut in about 2 cm lengths and placed the upside of leaves on glass of the standard cell of NIRS (diameter 3.5 cm) and covered the cell with a white seal. During preparation of cell samples it was checked for any gaps. If the white seal was visible in a gap more leaves were placed in the gap until upside of leaves were completely covering the cells. The upside of subclover leaves was placed in the standard cell of NIRS (diameter 3.5 cm) for making plant samples. Leaves from seeding plants of five pots of a group were cut and samples of each group of a study were made after mixing plants from different pots. It took approximately 5-10 minutes from collecting leaf samples to measuring their fresh weights and 30-45 minutes for spectral measurement using NIRS.

Plate 1-11: NIRS radiometer for spectral measurements

1.6.3 Nutrient Content

Plant material samples were collected at the same time as spectral readings were taken. The plant material samples were dried in an oven for 48 hours and 3 g of plant material was analysed for micro and macronutrients. Plant nutrient analysis of subclover including copper, zinc and molybdenum has been given in Table 1 and for annual ryegrass in Table 2. Wongan loam soil and white washed sand have been analysed for macro and micronutrients, pH and organic carbon. Wongan loam soil and washed white sand have been analysed for macro and micronutrients, pH and organic carbon (Appendix 1-2). There was a 0.06% copper and zinc in washed white sand as compared to 4.42% copper and 0.76% zinc in Wongan loam soil. Both soils were neutral and were not saline. Analysis of thrive solution applied to plants for germination is given in Appendix 1-3.

1.6.4 Water Content

It took approximately 5-10 minutes from collecting plant leaf samples to measuring their fresh weights by an electronic balance (accuracy of 0.01 gram) and immediately put in an air circulating oven. Fresh plant samples were weighed (Weight, FW) and then they were dried in an oven at 65°C until constant weight (Dry Weight, DW) was reached in 48 to 72 hours. The relative water content (RWC) was calculated using the following formula (Equation 1-1):

$$RWC = (FW - DW)/FW \qquad 1\text{-}1$$

Relative water contents of annual ryegrass and subclover on different dates are given in Table 1-3 and Table 1-4.

Table 1-1: Plant nutrient analyses of subclover

Date	30/01/2004	30/01/2004	5/03/2004	5/03/2004	5/03/2004	5/03/2004	15/03/2004	15/03/2004
Plant sample	SC-Low[a]	SC-All[b]	SC-Low	SC-All	SC-low-fresh[c]	SC-All-fresh	SC-Low	SC-All
Nitrogen (%)	3.04	2.88	N/A	2.31	4.25	4.22	5.69	5.61
Phosphorous (%)	0.327	0.334	0.316	0.349	0.384	0.364	0.427	0.474
Potassium (%)	1.726	1.436	1.197	1.565	3.186	2.996	3.167	3.193
Sulphur (%)	0.255	0.264	0.258	0.363	0.56	0.605	0.68	0.695
Sodium (%)	1.173	1.115	0.841	0.912	0.703	0.739	0.62	0.689
Calcium (%)	0.99	1.087	1.123	1.222	1.64	1.662	1.827	1.804
Magnesium (%)	0.307	0.309	0.26	0.285	0.377	0.41	0.435	0.428
Chloride (%)	1.733	1.951	1.182	1.387	2.667	2.48	2.642	2.907
Copper (mg kg^{-1})	16.29	16.58	12.44	14.55	15.71	17	23.4	22.32
Zinc (mg kg^{-1})	27.12	65.55	22.34	56.57	38.68	76.34	51.14	101.98
Manganese (mg kg^{-1})	22.7	27.7	30.4	21.3	46.9	55.3	67.4	71.3
Iron (mg kg^{-1})	99.9	82	95.2	77.9	107.8	98.5	142.2	148.9
Nitrate (mg kg^{-1})	107	62	114	89	598	400	726	1226
Boron (mg kg^{-1})	69	72.6	59.2	55.9	59.4	68.2	126	124
Molybdenum (μg kg^{-1})	3302	9881	5888	28540	1376	12342	452	17700

a Subclover without Cu, Zn & Mo

b Subclover with Cu, Zn & Mo

c Freshly grown Subclover without Cu, Zn & Mo

Table 1-2: Plant nutrients analyses of annual ryegrass.

Date	5/03/2004	5/03/2004	22/03/2004	22/03/2004
SAMPLE_ID	RG-Low	RG-All	RG-Low	RG-All
Nitrogen (%)	1.37	1.44	1.38	1.13
Phosphorous (%)	0.352	0.363	0.37	0.358
Potassium (%)	2.56	2.417	2.436	2.349
Sulphur (%)	0.226	0.243	0.2	0.221
Sodium (%)	0.362	0.336	0.578	0.485
Calcium (%)	0.687	0.758	0.675	0.777
Magnesium (%)	0.35	0.363	0.308	0.357
Chloride (%)	1.863	1.654	2.523	2.2
Copper (mg kg^{-1})	8.84	9.53	8.69	8.83
Zinc (mg kg^{-1})	24.51	47.53	29.76	51.79
Manganese (mg kg^{-1})	188.1	140.2	241	218.9
Iron (mg kg^{-1})	62.3	70.2	54.5	44.5
Nitrate (mg kg^{-1})	44	77	40	38
Boron (mg kg^{-1})	56.3	59	55.5	27.3
Molybdenum (µg kg^{-1})	2758	14644	1183	15012

Table 1-3: Plant water content of annual ryegrass and subclover groups on different dates

10/01/2004	Fresh Weight (g)	Dried Weight (g)	Relative Water Content (%)
Water stress	59.9	17.9	70.1
Waterlogged	55.0	17.0	69.1
Control	84.8	21.9	74.2
19/01/2004			
Water stress	58.1	21.5	63.0
Waterlogged	69.9	21.4	69.4
Control	77.0	24.7	67.9
31/01/2004			
Water stress	29.0	11.4	60.7
Waterlogged	36.5	13.3	63.6
Waterlogged in bin	28.2	10.9	61.3
Control	33.6	12.1	64.0
21/02/2004			
Water stress	39.2	15.5	60.5
Waterlogged	74.8	23.7	68.3
Waterlogged in bin	25.6	10.1	60.5
Control	82.3	24.1	70.7
Water stress low	55.4	18.5	66.6
26/02/2004			
Water stress	20.6	10.1	51.0
Waterlogged	28.3	10.9	61.5
Waterlogged in bin	16.0	7.6	52.5
Control	24.6	9.6	61.0
Water stress low	18.2	8.1	55.5
28/02/2004			
Water stress	20.2	10.3	49.0
Waterlogged	33.4	12.6	62.3
Waterlogged in bin	18.2	8.3	54.4
Control	44.0	13.9	68.4
Water stress low	26.1	10.9	58.2
5/03/2004			
Water stress	28.3	17.0	39.9
Waterlogged	29.2	14.7	49.7
Waterlogged in bin	28.8	14.5	49.7
Control	54.3	20.9	61.5
Water stress low	31.0	16.3	47.4

Table 1-4: Plant water content of annual ryegrass and subclover groups for micronutrients study on different dates

5/03/2004	Fresh Weight (g)	Dried Weight (g)	Relative Water Content (%)
RG-All	23.4	13.2	43.6
RG-Low	23.3	12.6	45.9
SC-All	25.8	13.5	47.7
SC-Low	24.0	13.5	43.8
SC-low-fresh	29.2	12.0	58.9
SC-All-fresh	35.8	13.0	63.7
15/03/2004			
MN-All	24.3	7.5	69.1
MN-Low	29.9	8.2	72.6
MN-Soil	26.9	8.4	68.8
22/03/2004			
RG-All	12.3	7.0	43.1
RG-low	19.8	9.6	51.5

1. 7 **Results and Discussion**

1.7.1 Drought Stress Study

Spectral signatures of annual ryegrass using NIRS under low drought stress (RWC, 63%), and waterlogging stress (RWC, 69.4%) and control (RWC, 67.9%) showed two absorbance peaks at 1,450 nm and 1,930 nm (Figure 1-1). Spectral curves of the four treatments of annual ryegrass under low drought stress, waterlogging stress, waterlogging stress in bins had the highest separability at 1,450 nm and 1,930 nm. At 1450 nm, control had the lowest absorbance peak, followed by waterlogging stress, low drought stress and waterlogging in bin. In case of 1,930 nm absorbance peak, control had the lowest peak, then low drought stress peak, waterlogging stress and waterlogging in bin stress. Figure 1-1 shows two absorbance peaks in the visible range at 454 nm and 672 nm. Three absorbance troughs are also visible at 546 nm, 1,682 nm and 2,226 nm. The separability of four treatments is not as visible at 546 nm as at 1,682 nm and 2,226 nm. The absorbance troughs at 1,682 nm and 2,226 nm show that control has the lowest absorbance and waterlogging in bins has the highest absorbance and waterlogging and low water stress lie in between these. This indicates that for detection of water and waterlogging stresses on pasture plants wavebands between 1,450 nm and 2,300 nm should be studied in detail. Although the positions of prominent liquid water absorptions are centered at 760 nm, 970 nm, 1,190 nm, 1,450 nm, 1,900 nm and 1,940 nm, the reflectances in these bands are quickly saturated and solely caused by changes in leaf water content (Elvidge, 1990). However, the reflectance absorptions in the 1,650–1,850 nm region reflect not only the leaf water content, but also the contents of leaf cellulose and lignin, and are directly related to the plant growing status (Curran, 1989 and Zagolski, 1996). The field spectrometer PIMA, which gave the reflectance between 1,300 nm and 2,500 nm could be used efficiently in the greenhouse for taking reflectance readings of plants in water stress study. This was also observed by other researchers that dehydration of plant leaves caused an increase in reflectance throughout the 400-2,500 nm region, but most significantly between 1,300 and 2,500 nm where strong absorption bands were located (Hunt and Rock, 1989; Carter, 1991; Hunt, 1991; Cibula *et al*., 1992 and Danson *et al*., 1992).

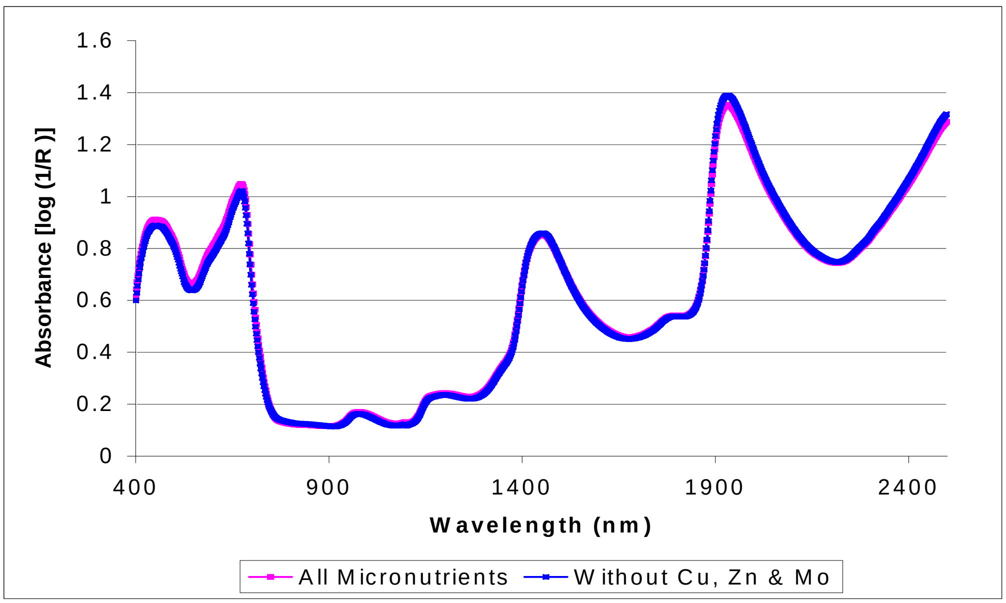


Figure 1-1 Spectral signatures of annual ryegrass under drought & waterlogging using NIRS on 19/01/04

Visual examination of spectral plots of annual ryegrass obtained by PIMA showed distinct reflection bands at 1,666 nm, 1,818 nm and 2,216 nm and absorption bands at 1,450 nm and 1,932 nm (Figure 1-2).

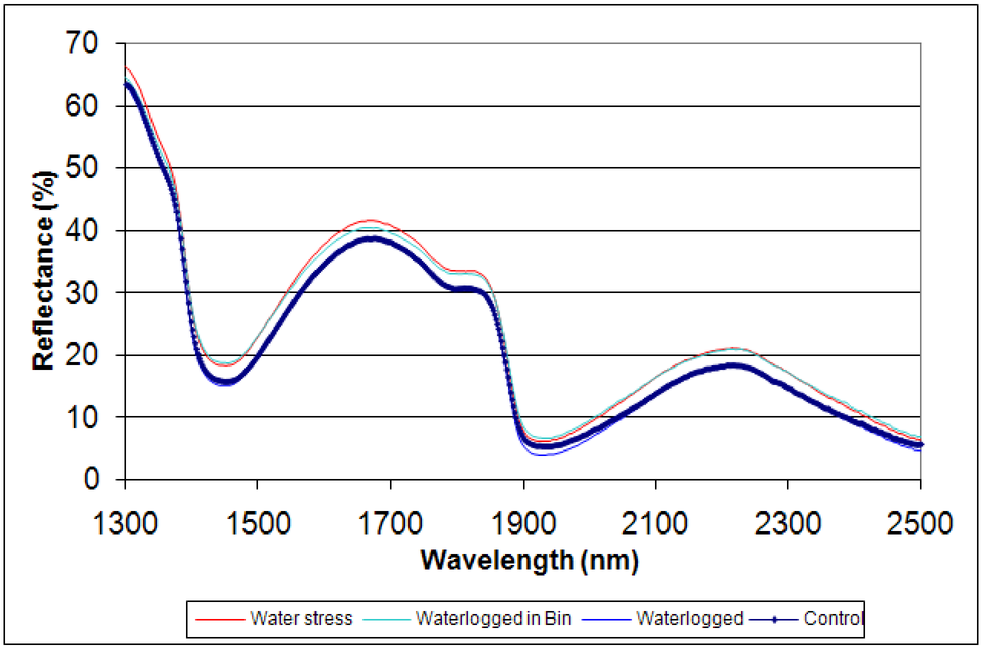


Figure 1-2: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 19/01/04

Figure 1-3 shows the average of four reflectance readings of control group (RWC, 64%), waterlogging group (RWC, 63.6%), waterlogging in bin group (RWC, 61.3%) and water stress group (RWC, 60.7%). Control group has the lowest reflection values followed by the waterlogging group, waterlogging in bin group and drought stress group have the maximum reflectance values between 1,300 nm and 2,500 nm. The highest separability based on magnitude among control, waterlogging and drought stress groups is located at reflection band at 1,666 nm, 1,818 nm and 2,216 nm and at 1,450 nm absorption band (Figure 1-3).

Figure 1-4, shows the average of five reflectance readings of control group (RWC, 70.7%), waterlogging group (RWC, 68.3%), waterlogging in bin group (RWC, 60.5%) and drought stress group (RWC, 60.5%). RWC of drought stress and waterlogging in bin groups is same but drought stress group has higher reflectance values. Over the period, average reflectance of drought stressed annual ryegrass increased at wavelengths 1,666, 1,818 and 2,216 nm with decrease in standard deviation (Table 1-5).

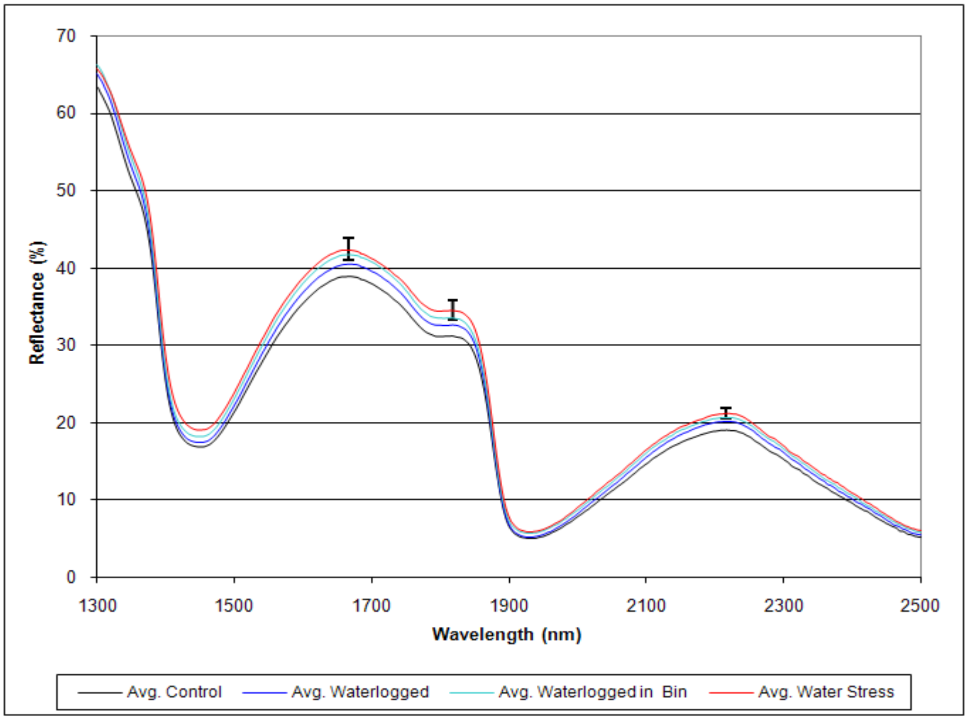


Figure 1-3: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 31/01/04

Table 1-5: Average reflectance of drought stressed annual ryegrass

Wavelength (nm)	Avg. Reflectance (%)	Std. Dev.	Avg. Reflectance (%)	Std. Dev.	Avg. Reflectance (%)	Std. Dev.
	31 January 2004		21 February 2004		28 February 2004	
1666	42.5	1.42	44.7	1.27	46.49	0.53
1818	34.6	1.27	36.5	1.25	37.9	0.72
2216	21.3	0.70	23.1	1.13	24.16	0.92

One week of dry spell was induced to five pots on 28 February 2004 and reflectance readings were taken on 5 March 2004. Drought stress group (RWC, 39.9%) has the highest reflectance of 48.2%, waterlogging group (RWC, 49.7%) with a magnitude of 43.1% reflectance and control group (RWC, 61.5%) has the lowest of 41.9% (Siddiqi *et al*., 2004).

The low RWC increased the reflectance values of drought stressed and waterlogged annual ryegrass plants over 1,300-2,500 nm range (Figure 1-7). Tian *et al*., (2001) also used the 1,650 to 1,850 nm absorption features to detect water deficiency in wheat leaves. Figure 1-7 shows the strongest spectral reflectance difference of annual ryegrass between 1,650 nm and 1,680 nm under drought & waterlogging. Relative water contents of annual ryegrass dried in an oven on different dates have been plotted against reflectance values of drought stressed annual ryegrass at three wavelengths 1,666, 1,818 and 2,216 nm (Figure 1-8). The average reflectance values increase with the decrease in relative water content in annual ryegrass plants.

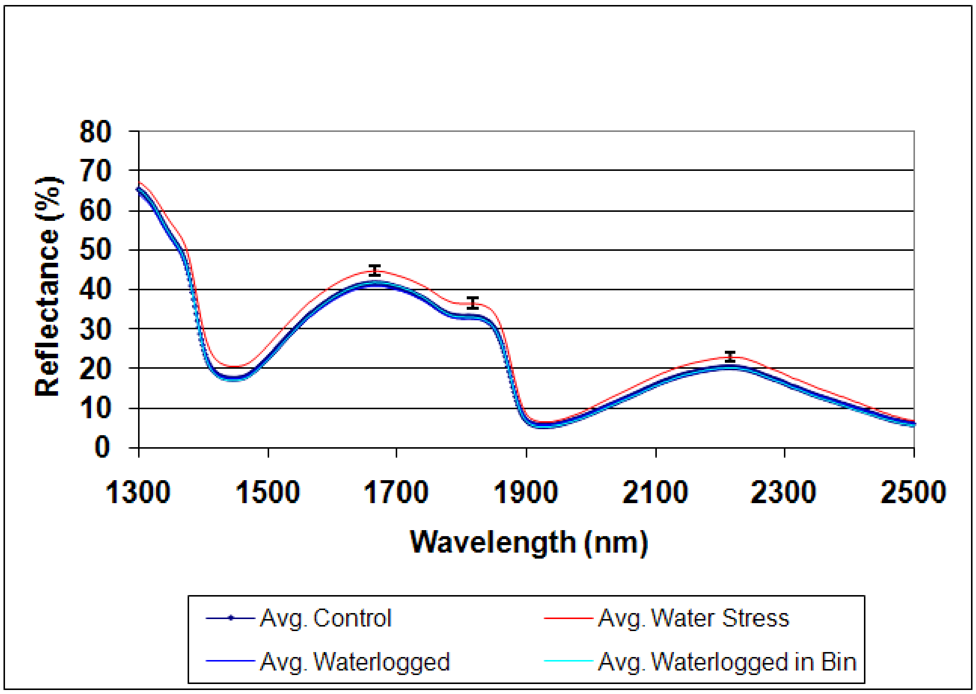


Figure 1-4: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 21/02/04

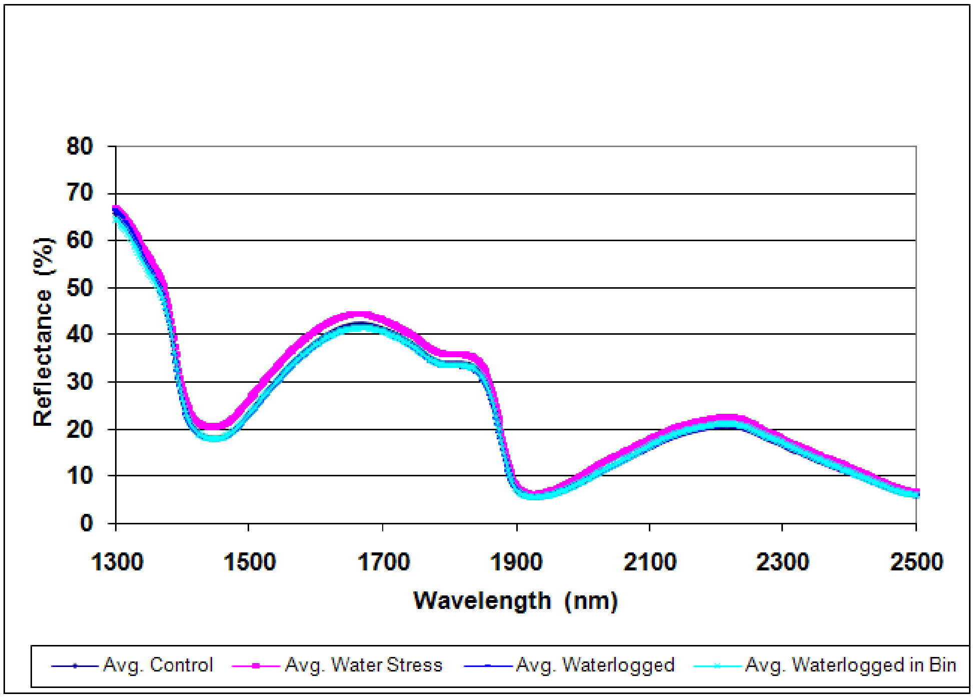


Figure 1-5: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 26/02/04

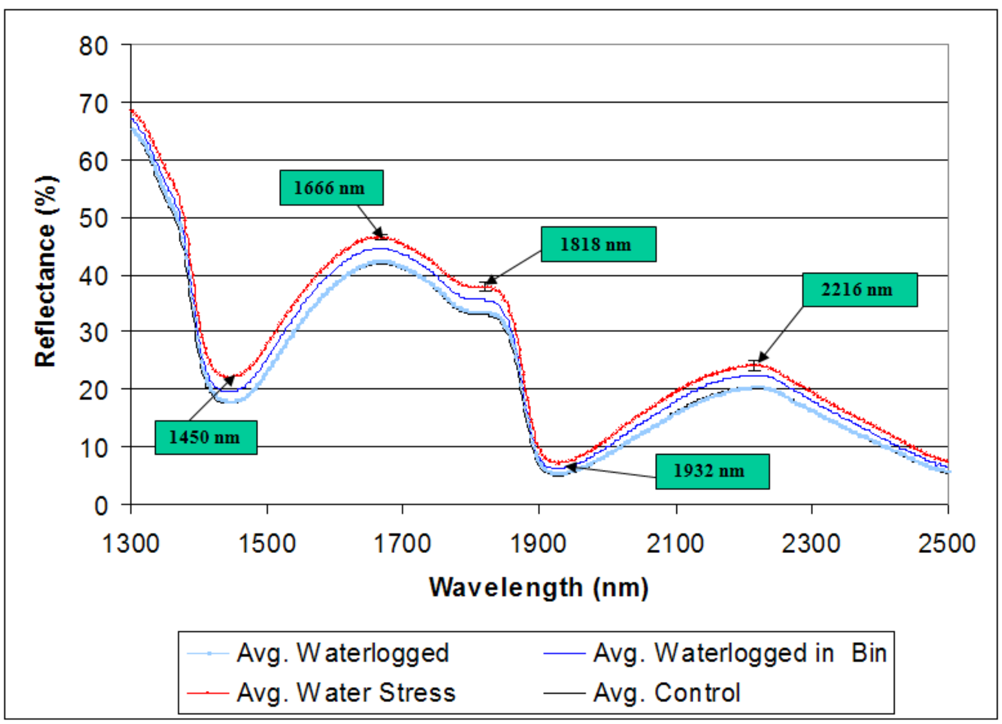


Figure 1-6: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 28/02/04

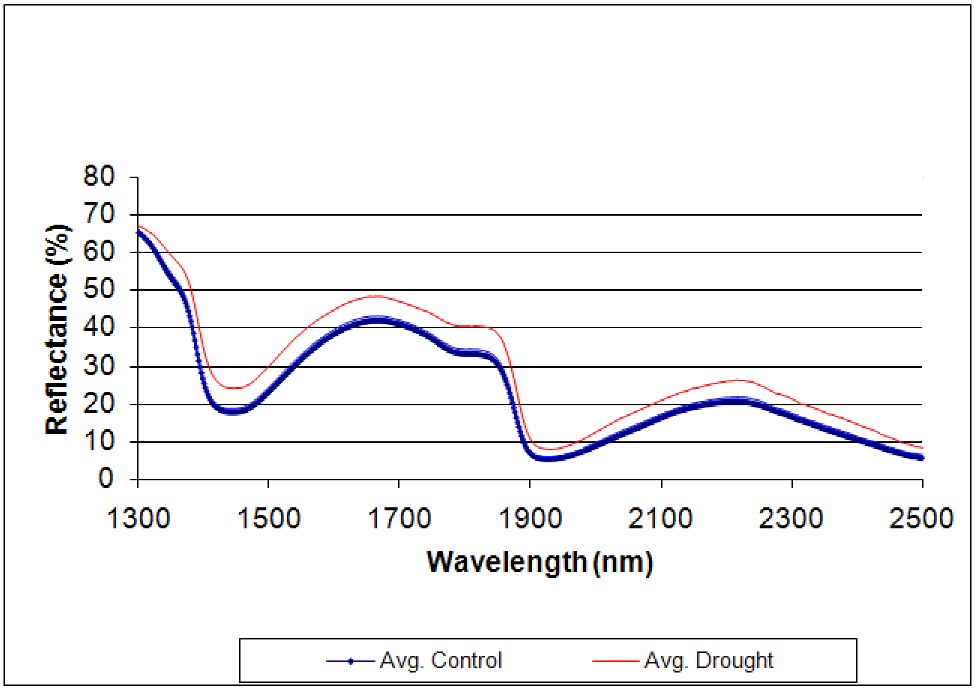


Figure 1-7: Spectral signatures of annual ryegrass under drought & waterlogging using PIMA on 05/03/04

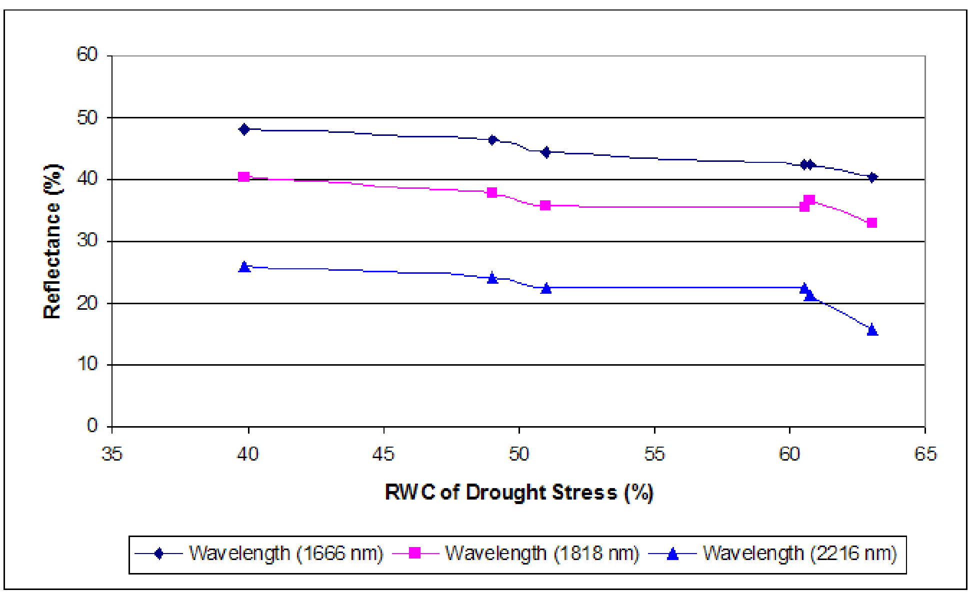


Figure 1-8: Reflectance against relative water content of drought stressed annual ryegrass at three wavelengths 1666, 1818 and 2216 nm

1. 8 **Data Analysis**

The design for this experiment was completely randomised design. The hypothesis for this study was whether the means of the reflectance between the drought stressed, waterlogged and control treatments of annual ryegrass are significantly different at each wavelength. The research hypothesis was statistically tested using one-way analysis of variance. The statistical tests were done at different time periods during the study to assess the spectral differences between treatments at different stages of the plants' physiological status (Table 1-6).

1.8.1 ANOVA test for drought waterlogging stress study

One-way ANOVA was used to test if the mean reflectances between the treatments were significant (Appendix 1-4). The research hypothesis, whether the means of the reflectance between the drought stressed, waterlogged and control treatments of annual ryegrass were significantly different at each wavelength. The null hypothesis of the test was, $H_o : \mu_1 = \mu_2 = \mu_3$ versus the alternate hypothesis $H_a: \mu_1 \neq \mu_2 \neq \mu_3$, where μ_1, μ_2 and μ_3 are mean reflectances of control, waterlogged and drought stressed groups at two reflection peaks of 1,666 nm and 2,216 nm. At 5% significance level reflection means of annual ryegrass at 1,666 nm wavelength and 2216 nm wavelength, are not equal to control and drought group’s reflection means and drought and waterlogging group’s reflection means except control and waterlogging groups in both of the cases (Figures 1-5 & 1-6). The fact that reflection means of control and waterlogging were not different showed that the waterlogged annual ryegrass survived well in waterlogged conditions. In conclusion, at the 5% significance level, reflection means at 1,666 nm wavelength and 2,216 nm wavelength are same in control and waterlogging groups.

1.8.2 Micronutrient Stress Study

Plant nutrient analyses of subclover over the period of the experiment shows that there was a twofold difference in zinc, more than 5 fold difference in molybdenum and no difference in copper concentration between subclover supplied with or without a fertiliser mix of copper, zinc and molybdenum micronutrients. Annual ryegrass also shows the similar trend (Tables 1-1 & 1-2).

Spectral signatures obtained by PIMA of annual ryegrass watered with all nutrients showed lowered reflectance values than annual ryegrass watered without copper, zinc and molybdenum. The spectral signatures obtained by NIRS of annual ryegrass watered with all nutrients showed higher absorbance values than annual ryegrass watered without copper, zinc and molybdenum between 400 nm and 674 nm in visible range and in SWIR range at 1944 nm band annual ryegrass watered with all nutrients showed lower absorbance values (Figures 1-9 to 1-12).

Spectral signatures obtained by NIRS of subclover watered with all nutrients showed lower absorbance (i.e. higher reflectance) values than subclover watered without copper, zinc and molybdenum between 450 nm and 700 nm in visible range and in SWIR region from 1,944 nm to 2,500 nm (Figures 1-13 to 1-15). The highest separability based on magnitude is located in visible region and it clearly shows absorbance peaks at blue (468 nm), red (674 nm) and SWIR range absorption peaks at 1,466 nm and 1,944 nm. Spectral plot showed that there are absorption troughs at green (560 nm), NIR (892 nm) and SWIR range (2,218 nm).

Spectral signatures obtained by NIRS of subclover after re-growth and watered with all nutrients showed higher absorbance values than subclover watered without copper, zinc and molybdenum in SWIR region from 1,420 nm to 2,500 nm with two distinct peaks at 1,468 nm and 1,948 nm (Figure 1-16). Spectral signatures obtained by NIRS of subclover after re-growth and watered with all nutrients showed higher absorbance (i.e. lower reflectance) peaks with highest separability at 468 nm and 678 nm and a trough centered at 560 nm than subclover watered without copper, zinc and molybdenum (Figure 1-17). In the SWIR region subclover watered without copper, zinc and molybdenum had a peak at 1946 nm (Figure 1-17).

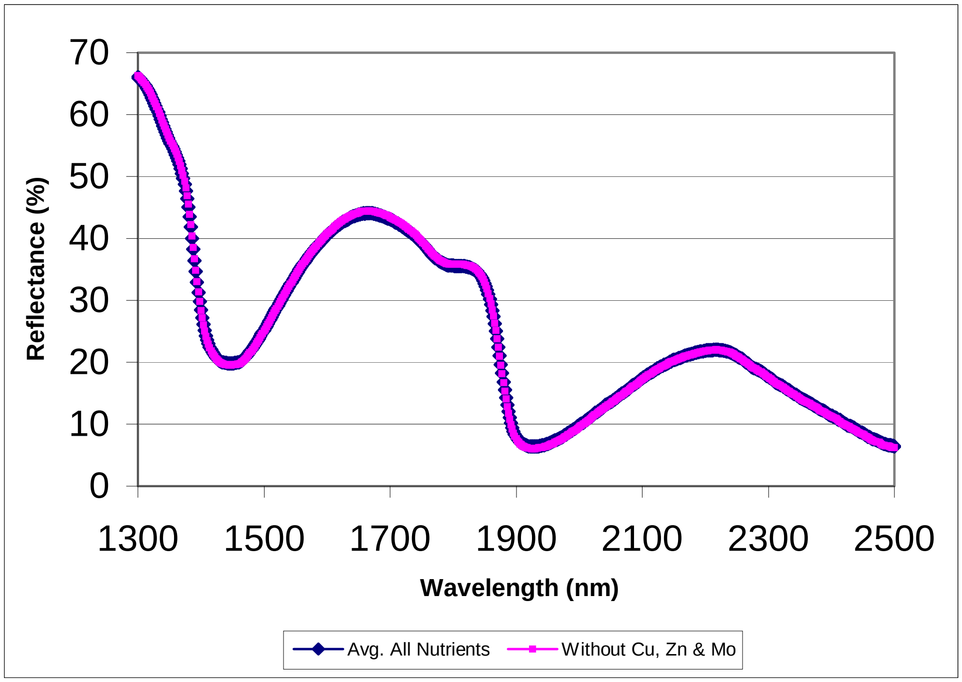


Figure 1-9: Spectral signatures of annual ryegrass using PIMA with or without copper, zinc and molybdenum on 05/02/04

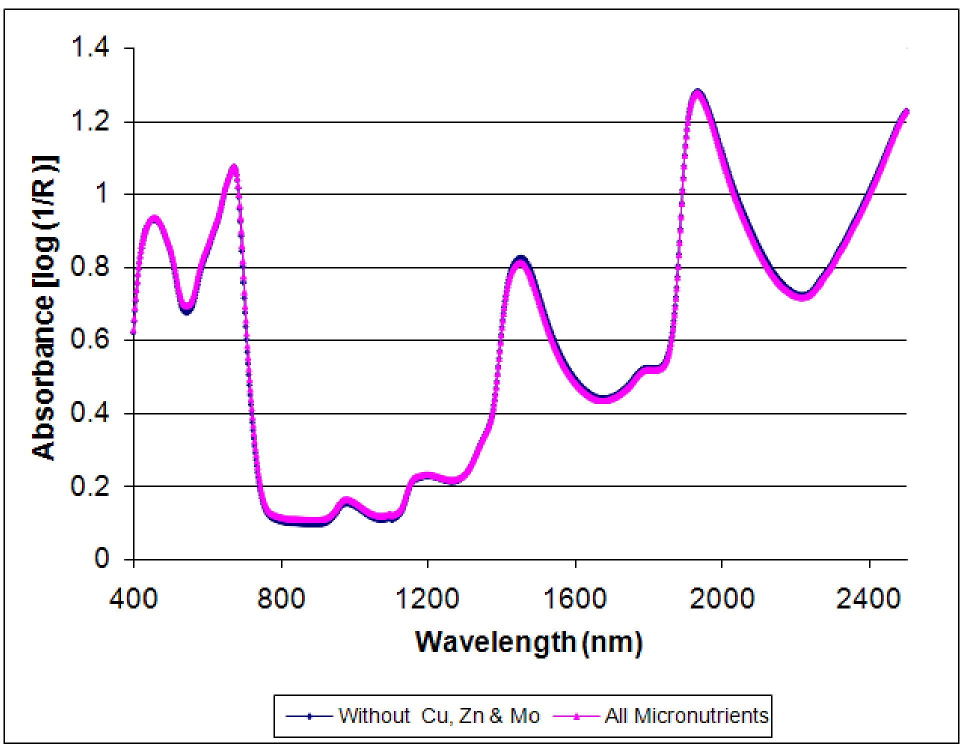


Figure 1-10: Spectral signatures of annual ryegrass using NIRS with or without copper, zinc and molybdenum on 05/02/04

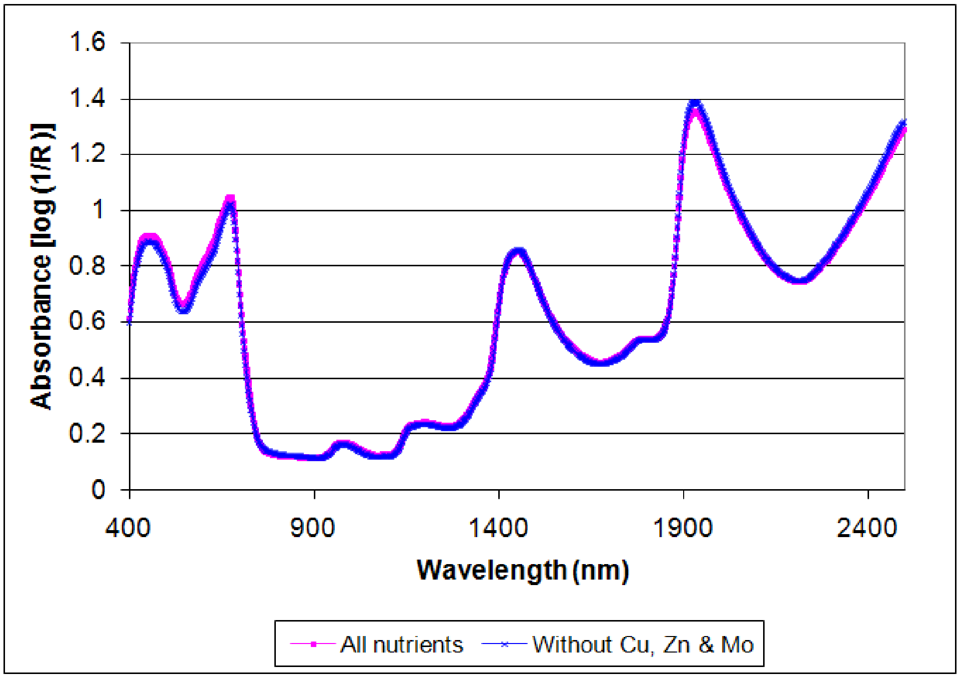


Figure 1-11 Spectral signatures of annual ryegrass using NIRS with or without copper, zinc and molybdenum on 15/02/04

Plate 1-12 Subclover in sand after germination

Plate 1-13 Subclover in soil after germination

Plate 1-14: Subclover in soil on 10/11/03

Plate 1-15: Subclover sown in sand for micronutrient Study

Plate 1-16: Subclover sown in soil (on front table) and in sand (at back tables) for micronutrient study

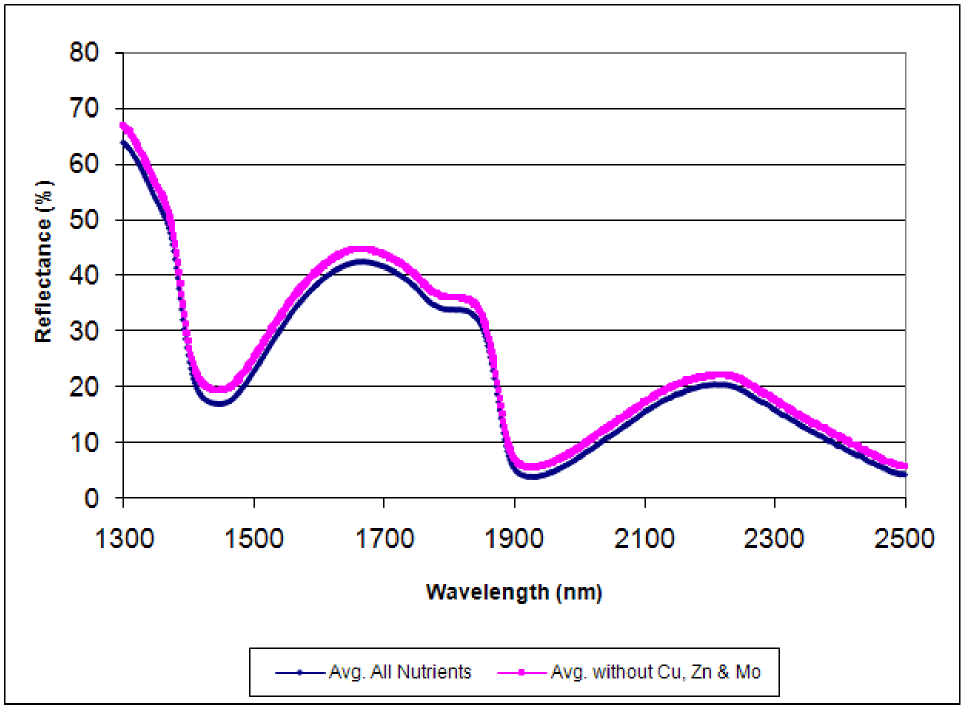


Figure 1-12: Spectral signatures of annual ryegrass using PIMA with or without copper, zinc and molybdenum on 21/02/04

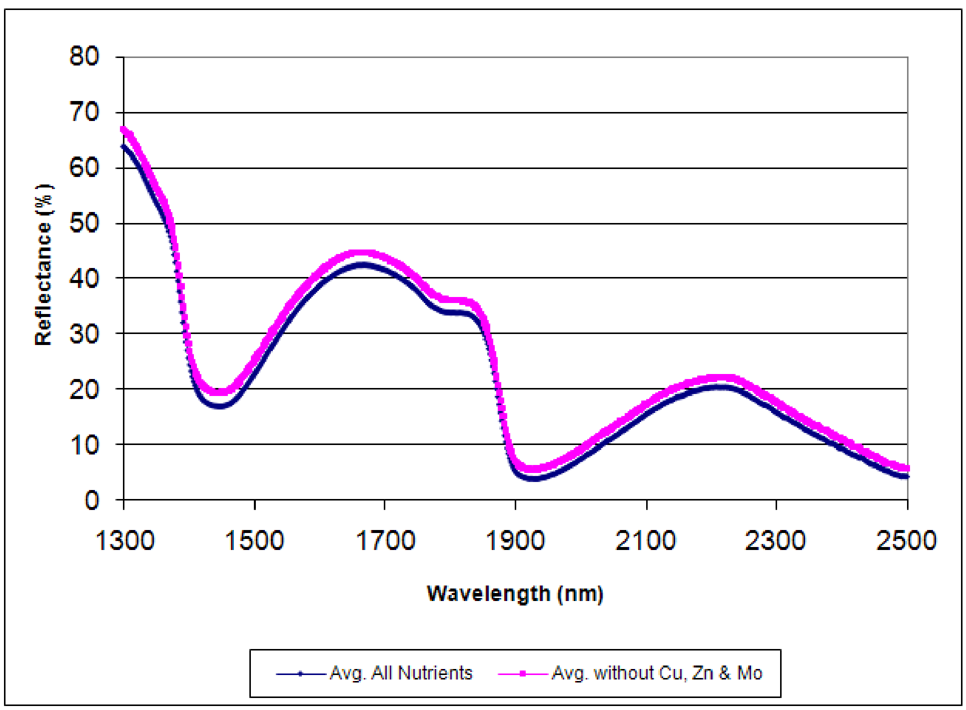


Figure 1-13: Spectral signatures of subclover using NIRS with or without copper, zinc and molybdenum on 05/03/04

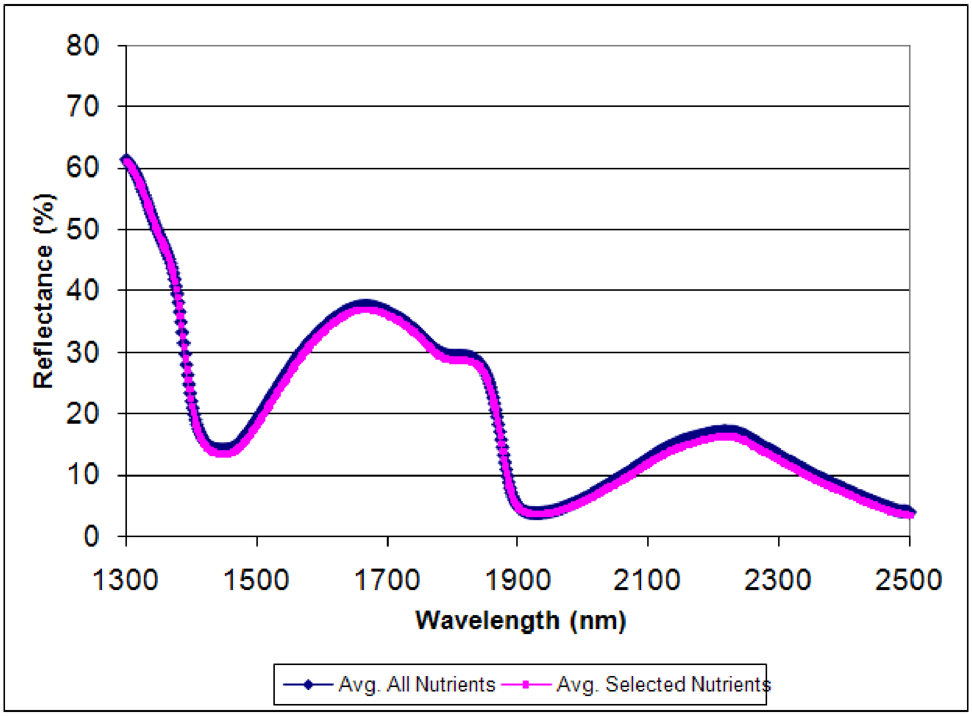


Figure 1-14: Average spectral signatures of subclover using PIMA with or without copper, zinc and molybdenum on 05/03/04

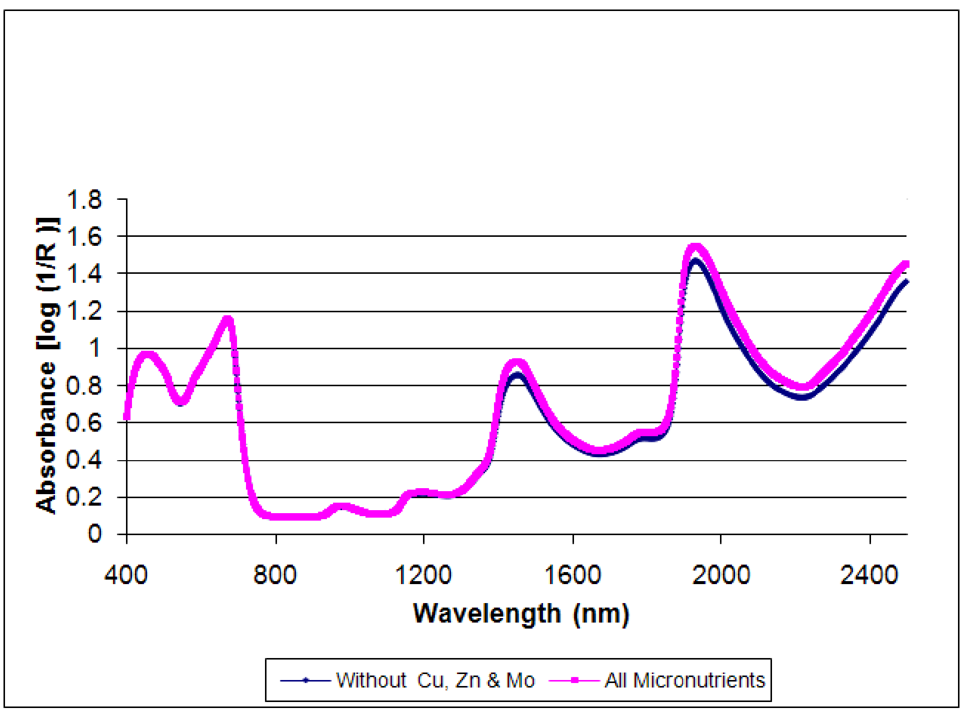


Figure 1-15: Average spectral signatures of subclover using NIRS with or without copper, zinc and molybdenum on 05/03/04

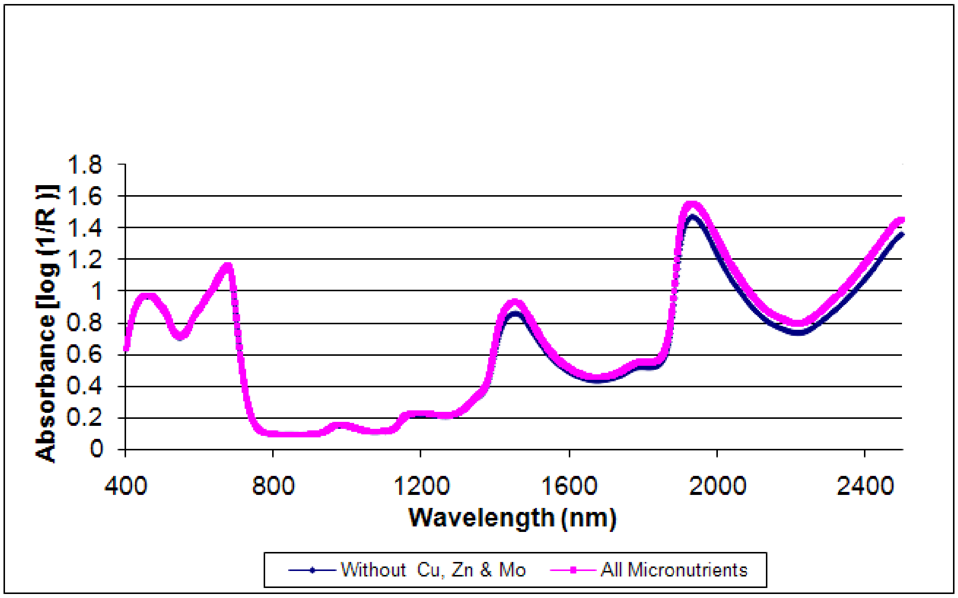


Figure 1-16: Spectral signatures of subclover after re-growth using NIRS with or without copper, zinc and molybdenum on 05/03/04

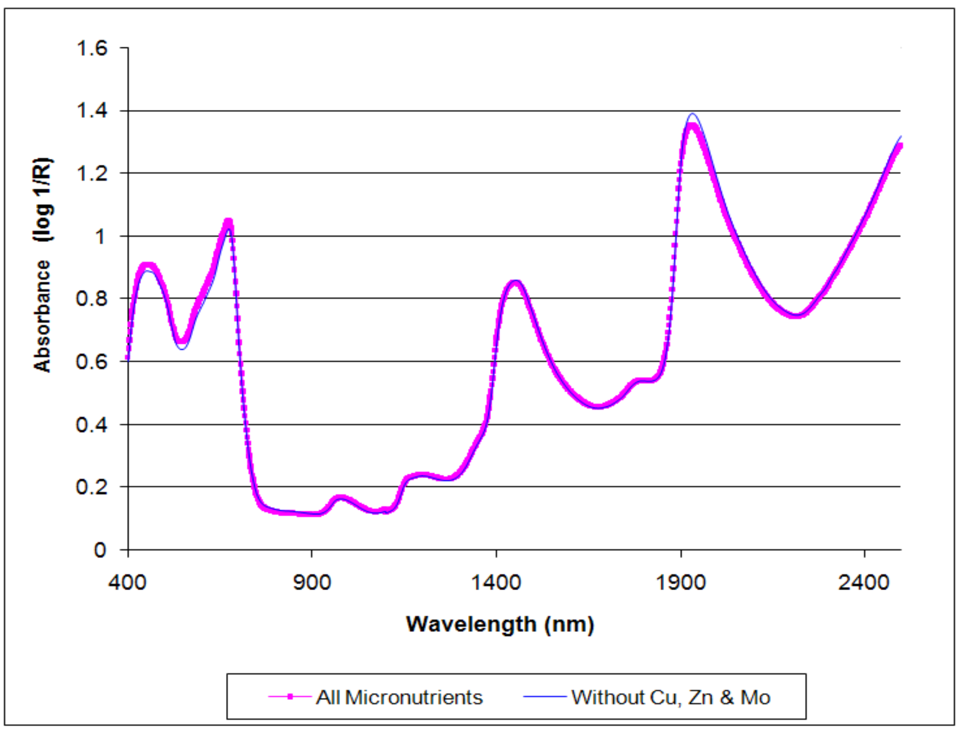


Figure 1-17: Spectral signatures of annual ryegrass using NIRS with or without copper, zinc and molybdenum on 22/03/04

1.8.3 ANOVA test for micronutrient stress study

At 5% significance level, absorption means of the hulls of subclover on 5 March, 2004 with low micronutrients using NIRS at 468 nm, 674 nm, 1,466 nm and 1,944 nm wavelength are equal to subclover with all micronutrients group's absorption (Figure 1-15). Similarly, at 5% significance level, absorption means of troughs of subclover with low micronutrients at 560 nm, 892 nm, and 2,230 nm wavelength are equal to subclover with all micronutrients group's absorption (Figure 1-15). In conclusion, at the 5% significance level, absorption means of subclover with low micronutrients at all wavelengths are same as that of absorption means of subclover with all micronutrients (Appendix 1-5).

1.8.4 Z-Test for Annual Ryegrass with all nutrients and low nutrients

The null hypothesis of paired z-test is that the difference between the two observations is 0. Based on the means of absorbance for annual ryegrass with all nutrients and with low nutrients using NIRS were almost the same on 22 March 2004 (Appendix 1-6). The variances in the two samples were not exactly the same.

The two-tailed p-value is given as 0.96, which is greater than 0.05, so the difference is not significant at the 5% level. In other words, we do not reject the null hypothesis.

1. 9 **Results and Discussion**

The study involved growing of two pastures species in controlled environment and use of two types of spectrometers to get spectral signatures. Some time was spent in the beginning of the experiment to get PIMA calibrated and looking for fertilisers for micronutrient study. To get better results from PIMA and NIRS some experimentation was done in the beginning of the experiment to get spectra of annual ryegrass and subclover of upside of leaves, downside of leaves and chopped samples of leaves. It was decided to get spectra of upside of leaves for comparison of spectra within group and between groups.

Drought, waterlogging and micronutrient stress was not applied in the early stages of annual ryegrass and subclover. This study was planned for use of hand-held spectroradiometer of spectral reflectance range of 400-2500 nm that was not available and PIMA and NIRS were used instead. Both, PIMA and NIRS spectrometers are not designed for taking spectral readings of fresh plants. The number of reflection and absorption readings using PIMA and NIRS were controlled by time in preparation of samples and taking readings single handily. The time and effort required in collecting the number of reflection and absorption samples could have been reduced if hand held spectroradiometer were available during the experiment. An experiment keeping in mind the shortcomings of the PIMA and NIRS could be designed for water stress or micronutrient stress for future research.

Subclover was planted in 30 pots in Wongan loam soil for water stress study but it did not germinate in fine textured soil and water stress could not be studied for subclover. The Wongan loam soil was brought from a farm 10 km west of Wongan Hills. It was scraped with a front-end dozer at a depth of 10 cm from the surface of the soil. Potting mix or sand should have been mixed with Wongan loam soil.

Aphids were seen in Subclover pots on 3 December 2003 and this problem persisted during the experiment as no insecticide could be used in the glasshouse because of CSIRO rules. Senescence of subclover planted in washed white sand started very rapidly and there was no chance of continuing the experiment for longer time. Air cooler in the glasshouse was faulty and it was not circulating water on hot days.

Spectral curves of annual ryegrass using PIMA showed distinct reflection bands at 1,666 nm, 1,818 nm and 2,216 nm and absorption bands at 1,450 nm and 1,932 nm (Figure 1-7). The highest separability based on magnitude among control, waterlogging and drought stress groups is located at reflection band at 1,666 nm, 1,818 nm and 2,216 nm and at 1,450 nm absorption band (Figure 1-7). Farmers can grow annual ryegrass in waterlogged areas especially in fine textured soils and aerenchyma properties of annual ryegrass should be studied in detail.

Subclover had good response in nutrient study when individual plants were compared (Figure 1-13). There was a 2 fold difference of zinc and more than 5 fold difference of molybdenum concentration between the treatments. Copper, zinc and molybdenum deficiency were studied together that made it impossible to see the effect of individual micronutrient on plants and relate it with changes in reflectance and absorbance.

Annual ryegrass had low response in nutrient study. Some techniques should be applied such as continuum removal of spectra to allow comparison of individual absorption features from a common baseline to see differences of reflectance under micronutrient study when absorption pits are enhanced and the absolute variance is removed.

The calculations appropriate for laboratory spectra with 10 nm resolution and 2 nm spacing may not be directly applicable to remote sensing data. Atmospheric absorptions, sampling positions and intervals will be different in the field. When vegetation cover is not completely covering the ground, soil and water background will also contribute towards remotely sensed signal.

Some of the results of spectral signatures in laboratory condition using hand held spectroradiometers are presented in the following section. Johns Hopkins University, USA measured the spectra of green and dry rye grass using a spectrometer GER IRIS Mark IV. The spectra comprised of two segments; the bidirectional VNIR and SWIR and the hemispherical MWIR and TIR. A piece of sod was illuminated from directly above and VNIR/SWIR spectrum was measured at a reflectance angle of 60 degrees to avoid viewing the hatch (http://shelbycountyswcd.org/ Workshop).

Bidirectional and directional hemispherical reflectance measurement of dry grass is given in Figure 1-18.

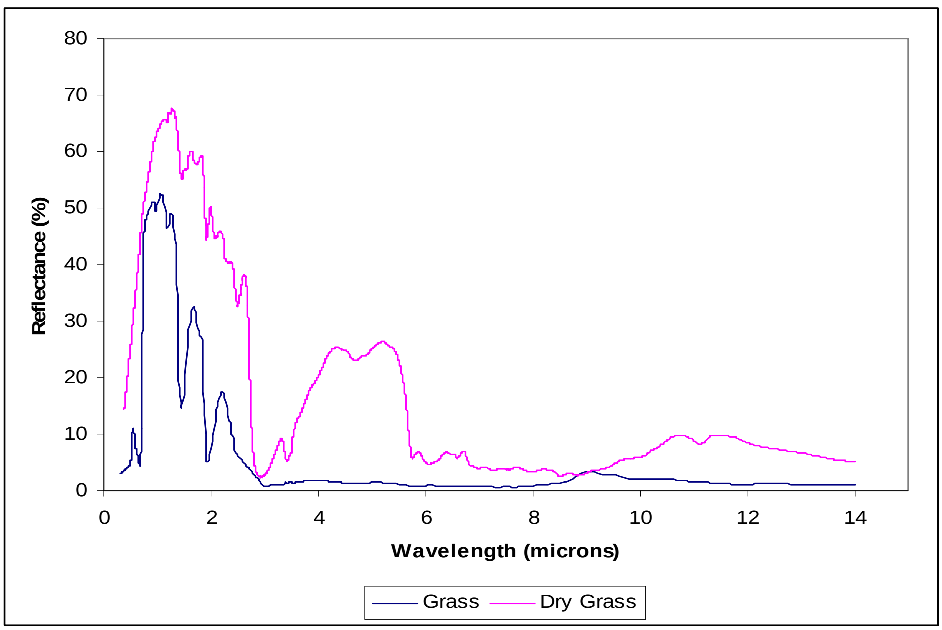


Figure 1-18 Spectral signature of green and dry grass measured by Johns Hopkins University, USA

Deciduous and conifer trees spectra were assembled from two segments; the VNIR and SWIR comprising segment one, and the MWIR and TIR comprising segment two (Figure 1-19). Both segments used leaf piles to simulate a canopy.

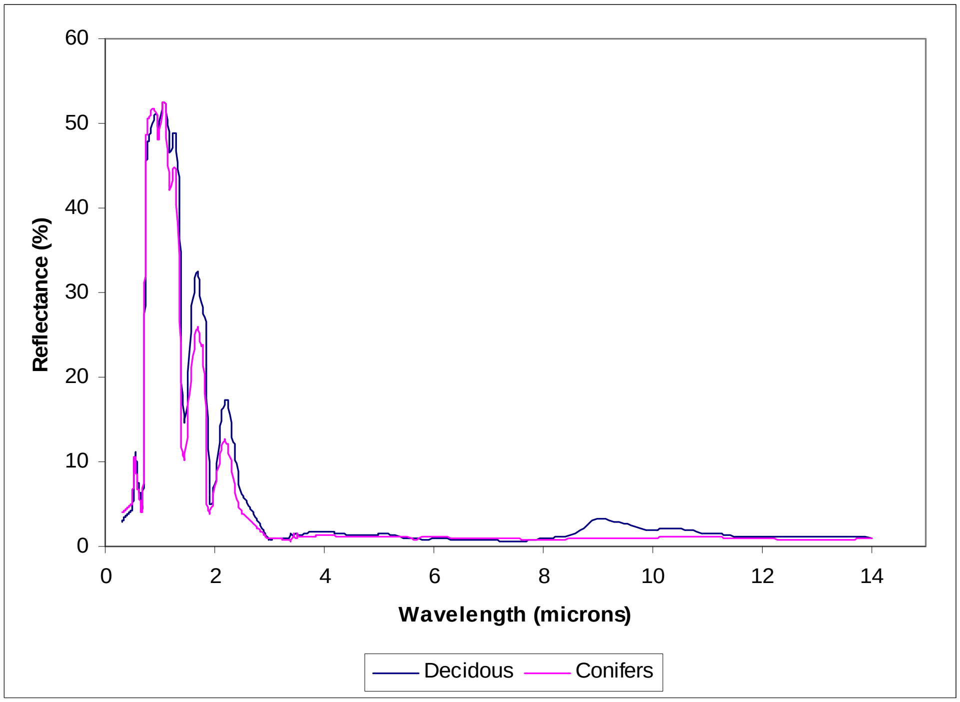


Figure 1-19 Spectral signature of deciduous and conifer trees measured by Johns Hopkins University, USA

Figure 1-20 shows spectral signatures of green and dry grass, soil and water from different sources are given by CSIRO (2002).

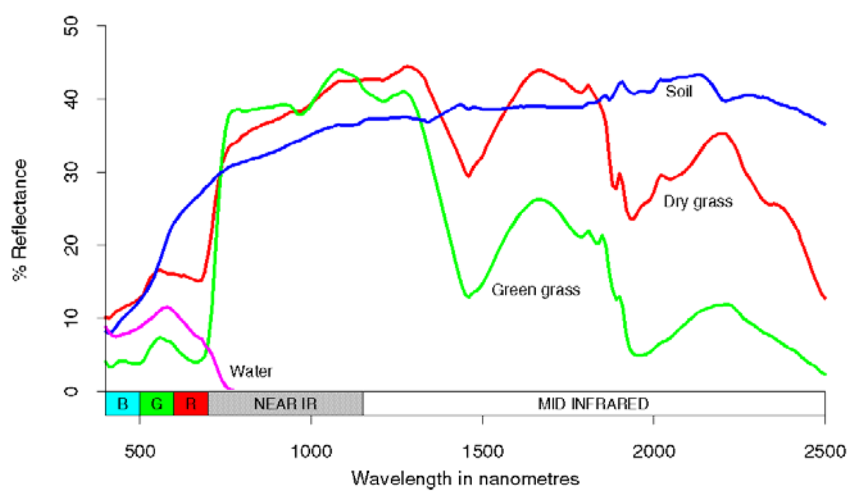


Figure 1-20 Spectral signatures of green and dry grass, soil and water CSIRO (2002)

Figure 1-21 shows spectral signatures of pinewoods, grasslands, red sand pit and silty water have been given by NASA (2002).

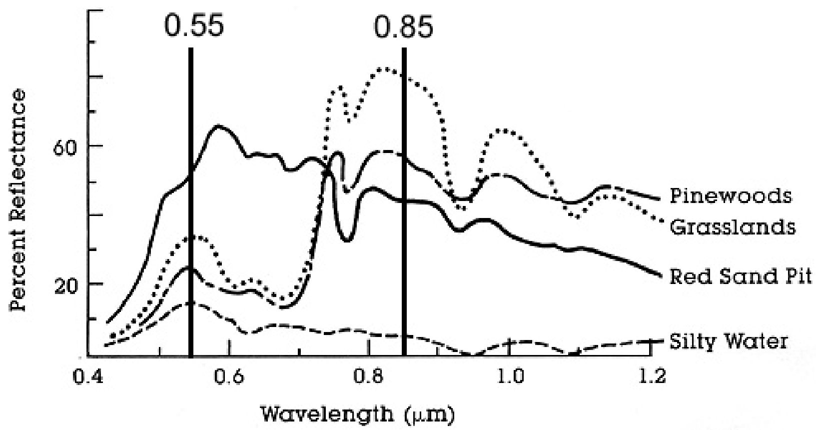


Figure 1-21 Spectral signatures of pinewoods, grasslands, red sand pit and silty water NASA (2002)

Jesen (1996) presented relative reflectance of the upper surface of a Sycamore leaf relative to MgO at different moisture contents and compared it with Thematic Mapper Bands (Figure 1-22).

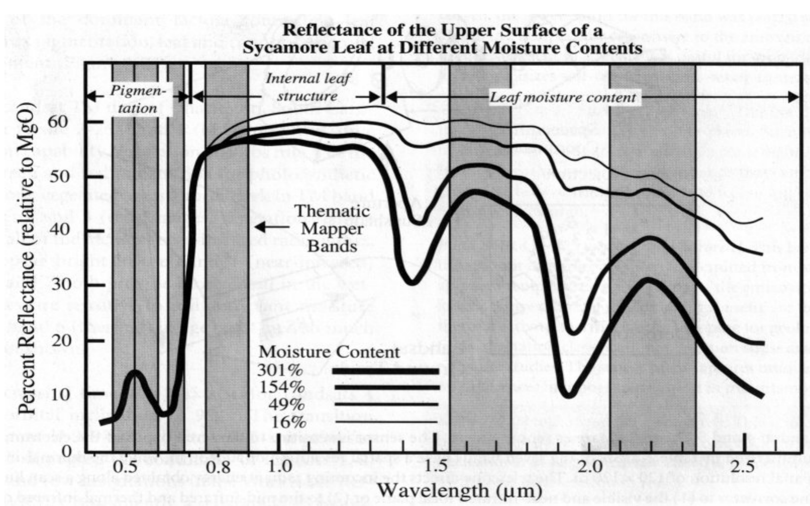


Figure 1-22 Relative reflectance of the upper surface of a Sycamore leaf relative to MgO at different moisture contents Jensen (1996).

Figure 1-23 shows USGS library spectra for polyhalite, gypsum, bassanite $2CaSO_4.H_2O$ and two salt crusts consisting of sodium chloride (halite) with minor amounts of various sodium, potassium, calcium and magnesium sulphates are illustrated by UNSW (http://www.bees.unsw.edu.au/school/staff/taylor/ salinity1 .html).

Saha *et al*., (1990) developed spectral signatures of salt affected and waterlogged land, wheat crop in good vigour and wheat crop in low vigour and settlement using Landsat TM bands in India (Figure 1-24). It was observed that bands 3, 4, 5 and 7 were poorly correlated and the spectral separability was greater in bands 4, 5 and 7 for all the wasteland categories. These spectral signatures can be used to delineate salinity areas in Wheatbelt of Western Australia.

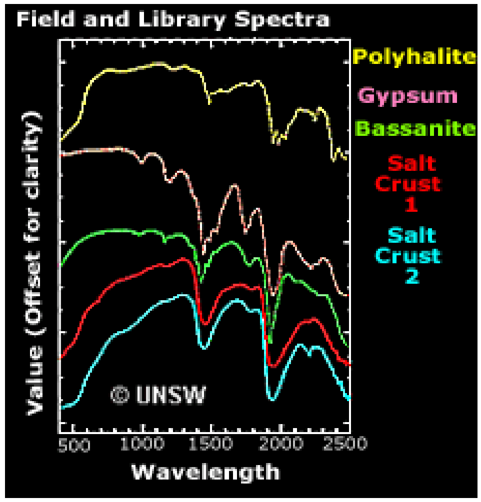


Figure 1-23 Spectra for polyhalite, gypsum, bassanite $2CaSO_4.H_2O$ and two salt crusts UNSW (2002)

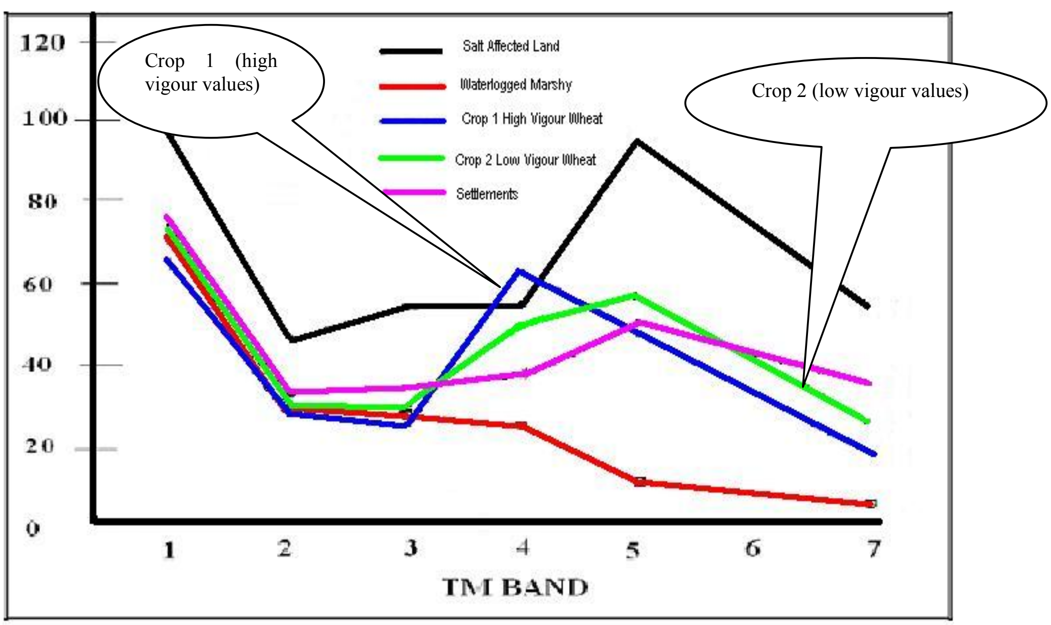


Figure 1-24 Spectral signatures of different wasteland categories and other Landuse features in India (after Saha *et al*., 1990)

2 USE OF GIS IN MONITORING DEEP DRAINS AT WHEATBELT OF WESTERN AUSTRALIA

2. 1 Introduction

The clearing of large areas in Wheatbelt have reduced evapotranspiration and increased recharge to shallow and deep groundwater and as a consequence ground watertable has risen (Allison and Hughes, 1983). The salts stored within the regolith as a result of rising watertables were remobalised, and the development of localised perched systems, has resulted in extensive areas of the Wheatbelt being affected by seasonal waterlogging and secondary salinity (McFarlane *et al*., 1992). In Western Australia dryland salinity affects 1.8 million ha of land and it is predicted that about 6.1 million ha may be affected to some extent in the future (Ferdowsian *et al*., 1996). The National Land and Water Resources Audit has identified that 4.3 million hectares (16%) of the south-west region have a high potential of developing salinity from shallow watertables and up to 8.8 million ha (33%) in Western Australia could be at high risk of developing shallow saline water tables by the year 2050 (http://audit.ea.gov.au/).

Department of Agriculture, WA estimates that there is waterlogging in one million ha of crops and 0.5 million ha of pastures in wet seasons to half of these areas in drier years in WA. These conditions affect the growth and development of the root system of the plants and can lead to severe yield losses. McFarlane and Williamson (2002) have identified three types of waterlogging. These are associated with perched aquifers in duplex soils, inundation of terraces and valleys, and saturation in surface soil due to the hydraulic pressure being above ground level in aquifers at the base of the regolith of highly weathered granites and gneisses or within channels in broad valley sediments. Waterlogging has reduced the potential yield by 30–80% for many crops and pastures in the areas with mean annual rainfall of more than 400 mm.

Surface drainage is the removal of excess water from the surface of the land by diverting it into improved natural or constructed drains, supplemented, when necessary, by the shaping and grading of the land surface towards such drams. Surface waters can be managed using a range of tools including grade banks, reverse interceptor banks, W-drains, spoon drains, permanent raised beds, constructed waterways and dams.

To remove excess water from the root zone and dissolved salts from soils, deep open drains are used which have depths varying from 1 to 3 m. Excess water in the landscape can also be managed by groundwater pumping. Both drainage and pumping can improve the outflow of water from both the saturated and unsaturated soil zones and reduce periodic seasonal events such as waterlogging and inundation. Groundwater pumping and deep open groundwater drains are used to reduce land salinisation at scales from managing local discharges to regional systems (Otto and Salama, 1994; Ali and Coles, 2001). Hatton (1999) recognised that engineering can be effective in reducing the impacts and extent of land salinisation on infrastructure and natural assets, as well as in keeping land under crops. Salama *et al*., (1997) used HARSD in combination with Flownet to estimate the changes in salinity risk associated with large-scale reforestation in south-eastern Australia.

Deep open drains were constructed in the late 1970s in the Moora district (Coles *et al*., 1999). Deep open drains to reduce land salinisation in local and intermediate scaled groundwater systems have been reported by several researchers (Bettenay 1978; George and Nulsen, 1985; Salama *et al*., 1994; Otto and Salama, 1994 and Ali and Coles, 2001). George (1991) recorded radial effects of greater than 100 m in deep open and tile drains in yellow earth on hill slopes in the eastern Wheatbelt. Drains now exist in almost every catchment of the Wheatbelt. The total length of these drains now exceeds 15,000 km but almost all of them have been constructed without any formal evaluation of their impacts on hydrology and ecology of the downstream rivers and streams that receive the drainage discharge from these drains. Currently most drains discharge into local creeks or salt lakes or even at the farm fence.

Speed and Simons (1992) reported radial effect of 10 m of shallow open drains (<1.5—1.8 m) in heavy textured, dispersive, and low permeability soils with little effect on watertables. Between 1996 and 1999, 266 Notices of Intent have been lodged with the Commissioner of Land to drain in excess of 50,000 hectares of land.

2. 2 **Research Method**

The objective of this study is to use remote sensing and GIS techniques to identify deep drains in the landscape and to analyse groundwater level data and study off-site and downstream ecological and hydrological impacts of drainage water discharge into natural streams and rivers in the Wheatbelt of WA.

2.2.1 Study Area Description

Two major drainage districts in Wheatbelt of Western Australia have been selected for monitoring efficacy of deep open drains in mitigating the problems of waterlogging and salinity in the area (Figure 2-1). Dumbleyung (Lat. 33.3 Long. 117.7) is located 268 km south-east from Perth. The deep drainage site is located 11 km north-east of Dumbleyung on Beynon Road. Dumbleyung site is situated at the headwaters of the Dumbleyung River. The property is in the lower-reaches of the Dorodine sub-catchment, within the Lake Dumbleyung catchment.

The town of Narembeen is located 280 km east of Perth. Narembeen (Lat. 32.1 Long. 118.4) is situated across the Avon River catchment. Land use in the district is predominantly wheat and barley in rotation with pastures and lupins (Ali et al., 2004a). Soils within the drainage area were described by Ali *et al*., (2004a) as duplex with loamy sand underlain by sandy clay.

2.2.2 Climate

The two deep open drainage sites Dumbleyung and Narembeen selected for this study have Mediterranean climate which is characterised by hot dry summers and cool wet winters. Most rain is caused by the passage of cold fronts between May and October, with less frequent summer thunderstorms. During winter (May to October) cold fronts pass through these sites and bring about 85% of mean annual rainfall. In summer the easterly airflow is from the dry interior out of reach of humid air.

The average annual rainfall for Narembeen is 334 mm with a minimum annual rainfall of 176 mm and a maximum rainfall of 588 mm from 1877 to 2007 (Figure 2-2).

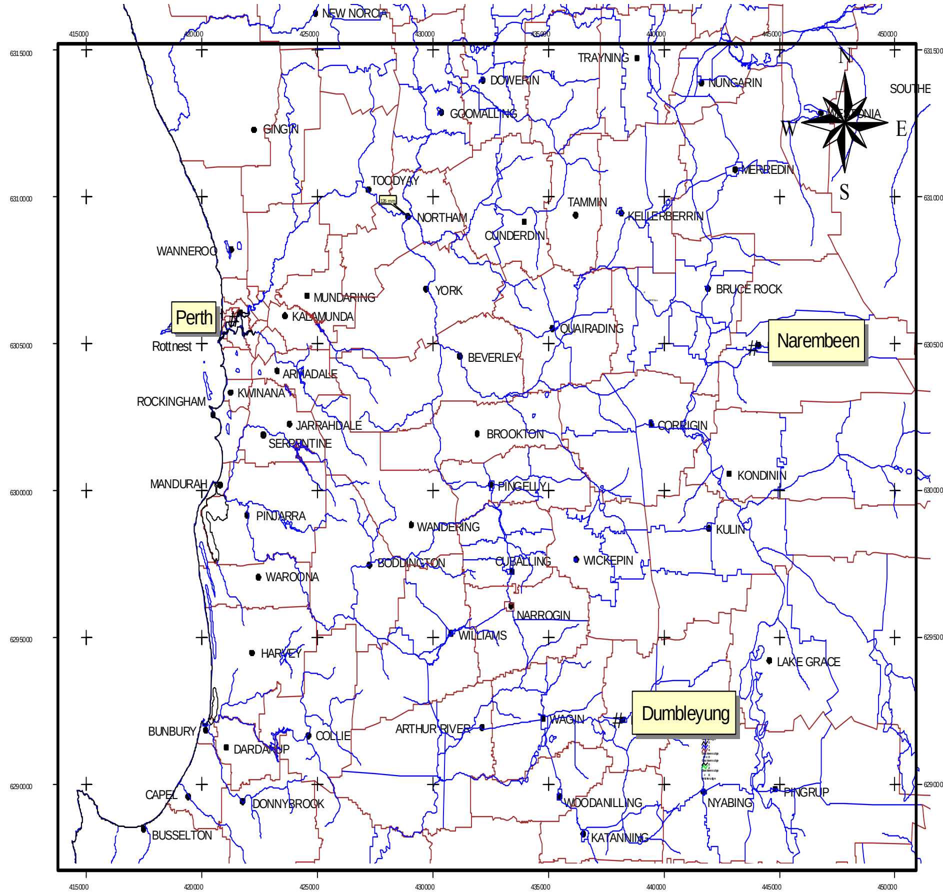


Figure 2-1 Locations of Deep Drainage Monitoring Sites

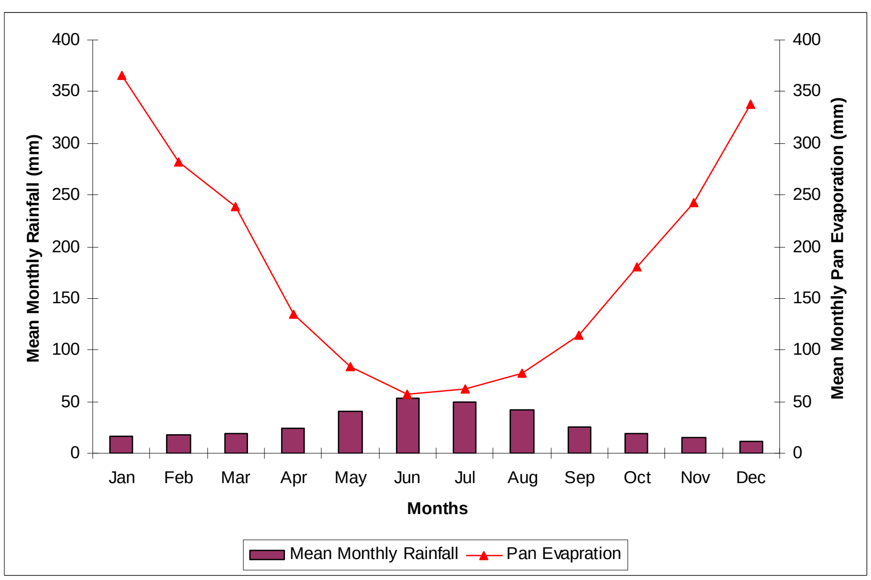


Figure 2-2 Mean Monthly Rainfall and Pan Evaporation recorded at Narembeen

2.2.2.1 Cumulative Deviation from Mean Rainfall (CDFM)

The CDFM technique shows the cumulative deviations of monthly, seasonal and annual rainfall pattern. In the CDFM analysis, the actual rainfall in a month, a season and a year is subtracted from its long-term average and a graph is prepared of cumulative deviation of rainfall from mean of that period against time. Yesertener (2005) has used this technique for studying rainfall trends and how it is related to groundwater fluctuations.

The CDFM analysis for Narembeen shows a long dry period from 1932 to 1962 and a wet period between 1963 and 1978. Annual rainfall has been decreasing since then with a wet period from 1992 to 1993 and a wet period from 1999 to 2001 (Figure 2-3). Monthly rainfall totals from 1998 to 2008 show an extremely high rainfall month total of 171.7 mm in January, 2000 in Narembeen which caused flooding in the area and deep drains were filled with sediments (Figure 2-4).

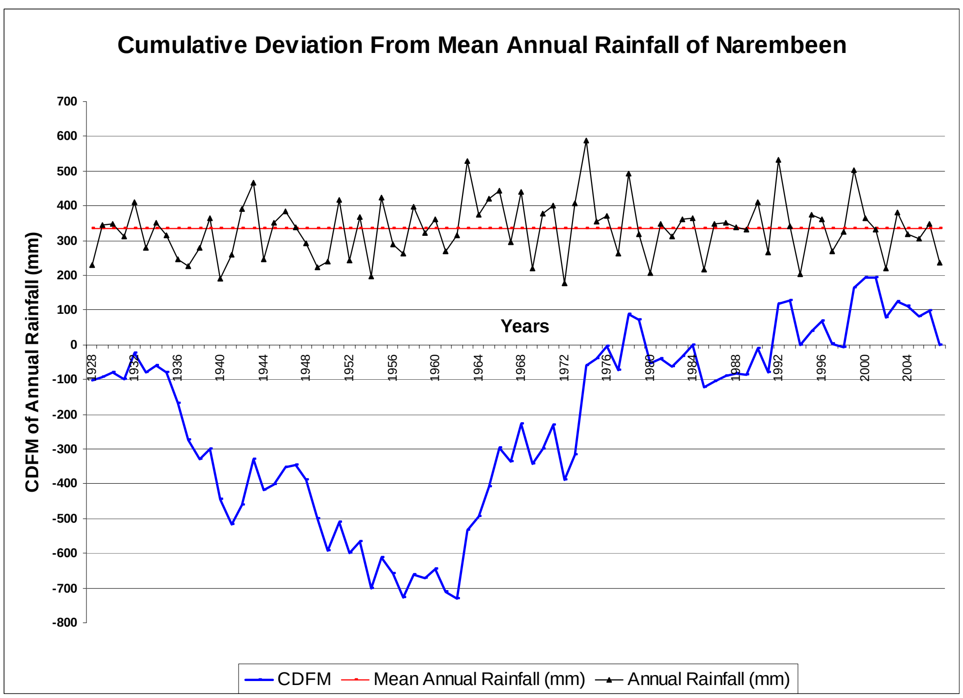


Figure 2-3 Cumulative deviation from mean (CDFM) with annual rainfall from 1877 to 2007 for Narembeen

Daily rainfall data of Narembeen from 1928 to 2007 were analysed to calculate frequency of rainfall events of 25 mm, 50 mm, 100 mm and 150 mm in seven days duration. The rainfall events of 25 mm in seven days duration from 1928 to 2007 with a decreasing trend line for Narembeen are given in Figures 2-5.

The rainfall events of 50 mm in seven days duration have decreased in the recent past which may result in low groundwater recharge in Narembeen (Figures 2-6). There were only four rainfall events of 100 mm or more in seven days in 1970, 1978, 1990 and 2000 in Narembeen (Figures 2-7). There were no rainfall events greater than 150 mm in seven days duration

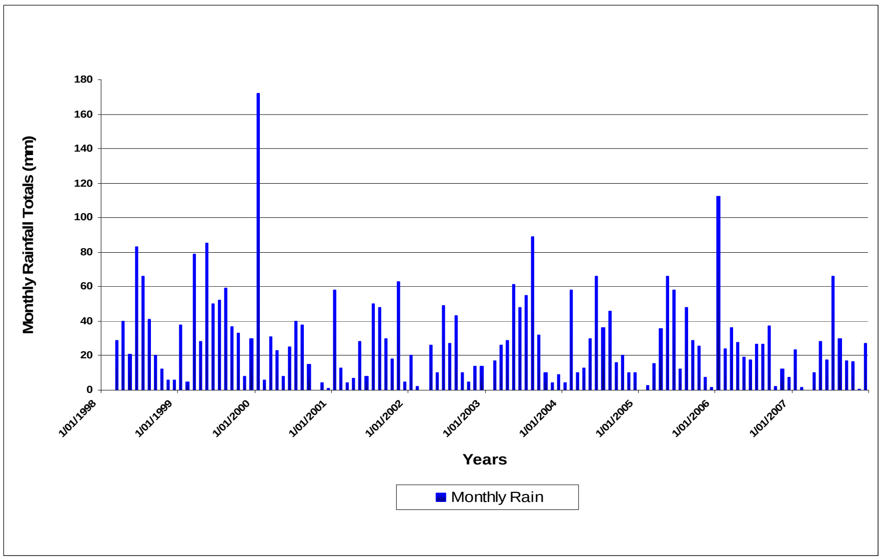


Figure 2-4 Monthly rainfall totals for Narembeen from 1998 to 2008

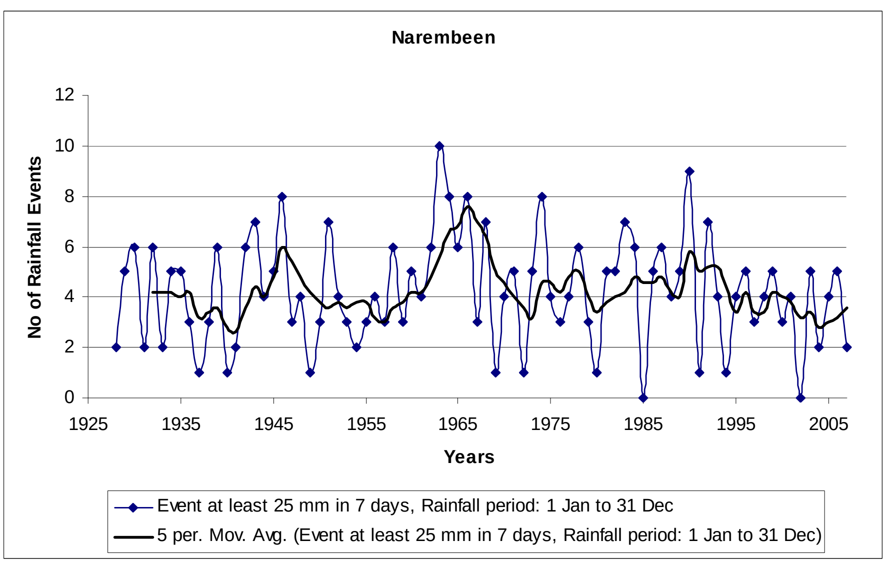


Figure 2-5 The rainfall events of 25 mm in seven days duration from 1928 to 2007 with trend line for Narembeen

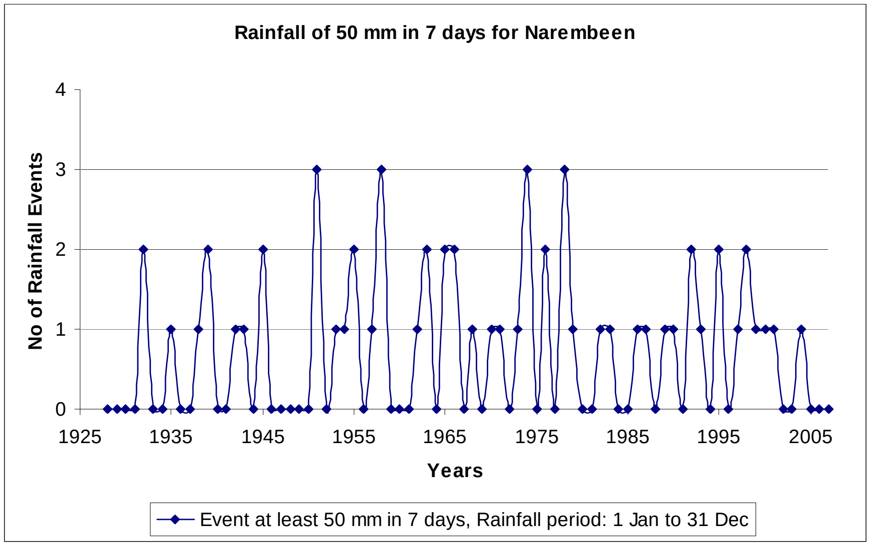


Figure 2-6 The rainfall events of 50 mm in seven days duration from 1928 to 2007 for Narembeen

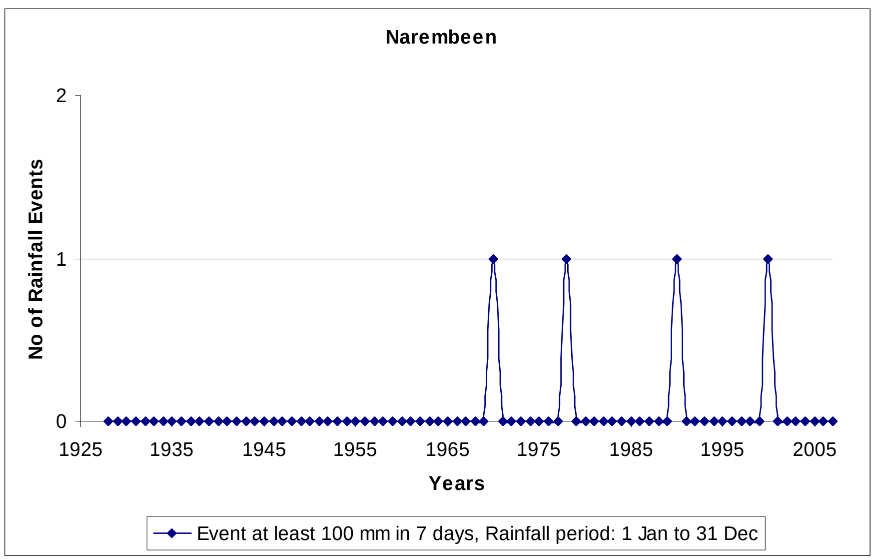


Figure 2-7 The rainfall events of 100 mm in seven days duration from 1928 to 2007 for Narembeen

The average annual rainfall for Dumbleyung is 388 mm with a minimum annual rainfall of 194 mm and a maximum rainfall of 631 mm from 1877 to 2007 (Figure 2-8). Average weekly rainfall and evapotranspiration for Dumbleyung is given in Figure 2-9

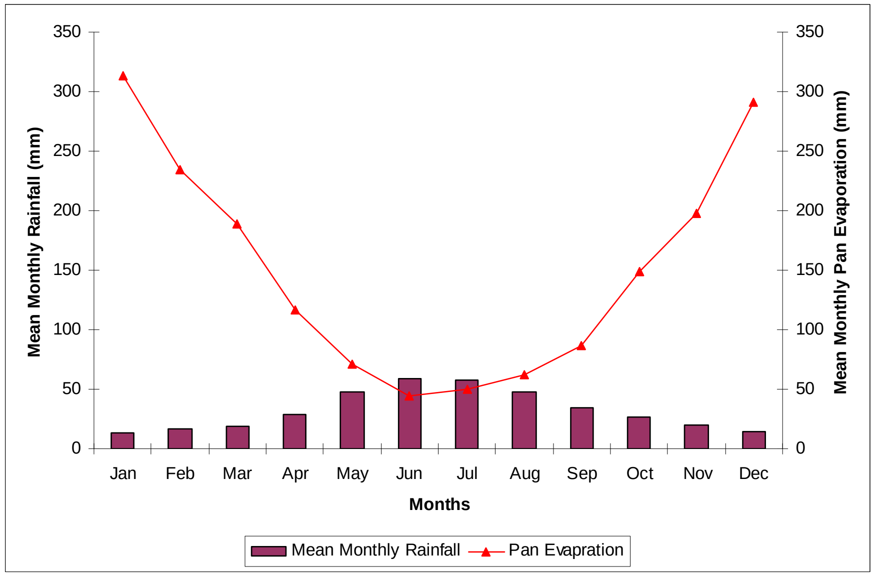


Figure 2-8 Mean Monthly Rainfall and Mean Monthly Pan Evaporation recorded at Dumbleyung.

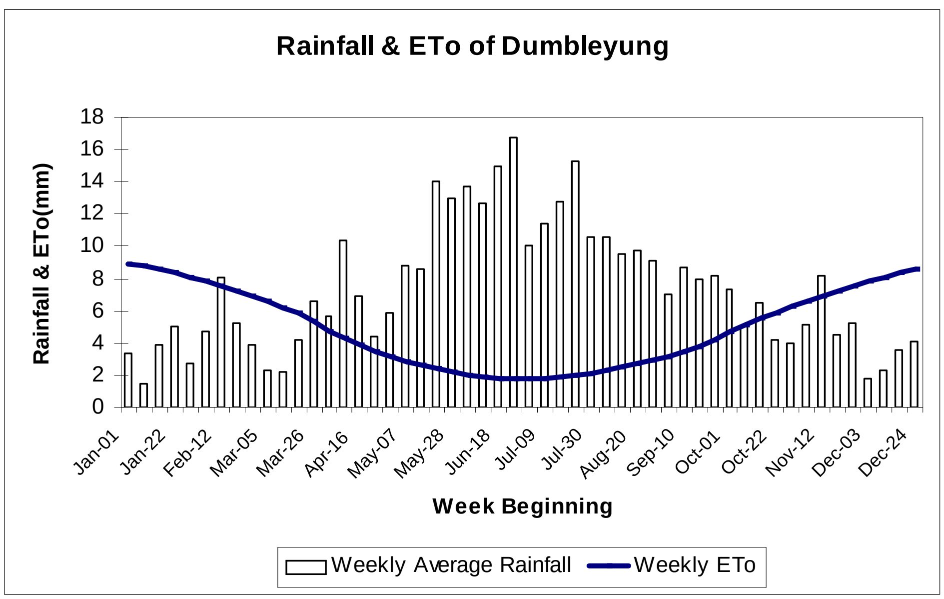


Figure 2-9 Average weekly rainfall and evapotranspiration for Dumbleyung

The CDFM analysis for Dumbleyung shows a wet period from 1915 to 1943, a mix of dry and wet periods between 1944 and 1993 and since 1994 annual rainfall is decreasing rapidly (Figure 2-2).

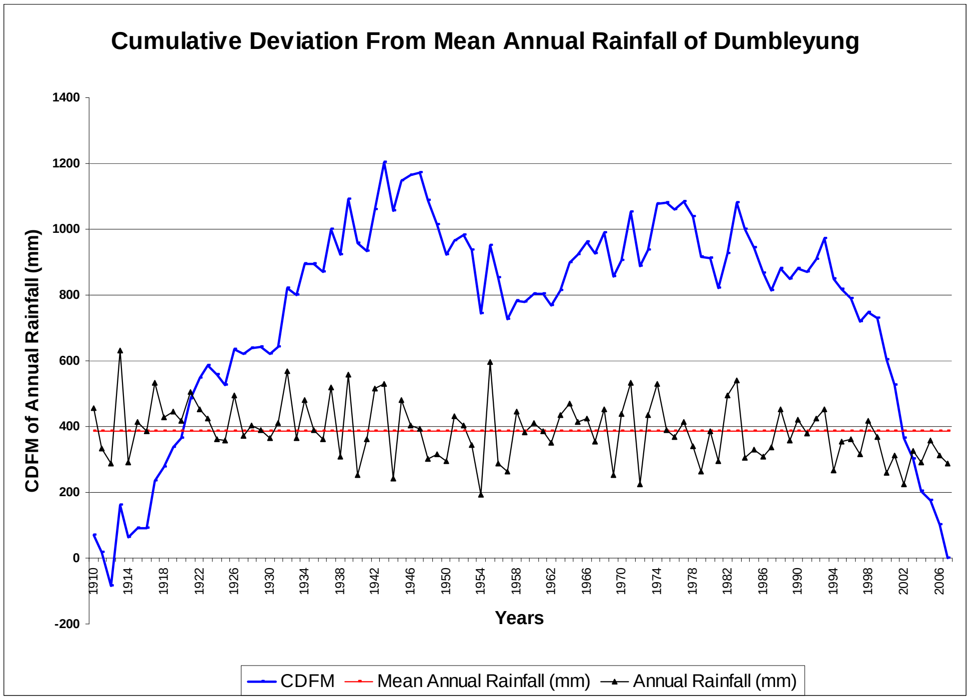


Figure 2-10 Cumulative deviation from mean (CDFM) with annual rainfall from 1877 to 2007 for Dumbleyung.

Daily rainfall data of Dumbleyung from 1910 to 2007 were analysed to calculate frequency of rainfall events of 25 mm, 50 mm, 100 mm and 150 mm in seven days duration. The rainfall events of 25 mm in seven days duration from 1928 to 2007 with a decreasing trend line for Dumbleyung are presented in Figures 2-11.

The were no rainfall events of 50 mm or greater in seven days duration for five consecutive years from 2000 to 2004 and again in 2007 which might have resulted in low groundwater recharge in Dumbleyung in the recent past (Figures 2-12). There were five rainfall events of 100 mm or more in seven days in 1913, 1934, 1937, 1955 and 1982 from 1910 to 2007 in Dumbleyung (Figure 2-13).

There were only two rainfall events of 150 mm or more in seven days in 1913 and 1955 from 1910 to 2007 in Dumbleyung (Figure 2-14). Monthly rainfall totals were low in 2001 and 2002. A monthly rainfall total of 107 mm occurred in April, 2005 that was more than 95th percentile and it might have recharged the groundwater in Dumbleyung.

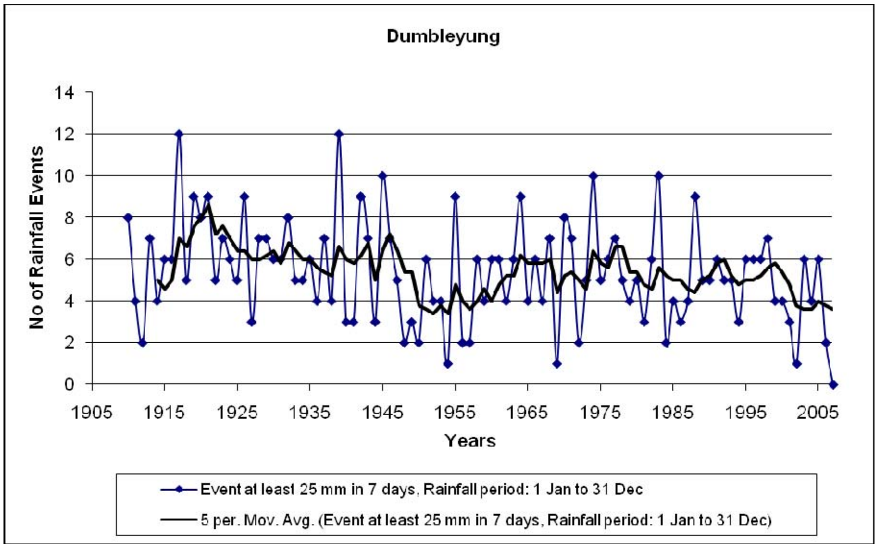


Figure 2-11 The rainfall events of 25 mm in seven days duration from 1910 to 2007 for Dumbleyung

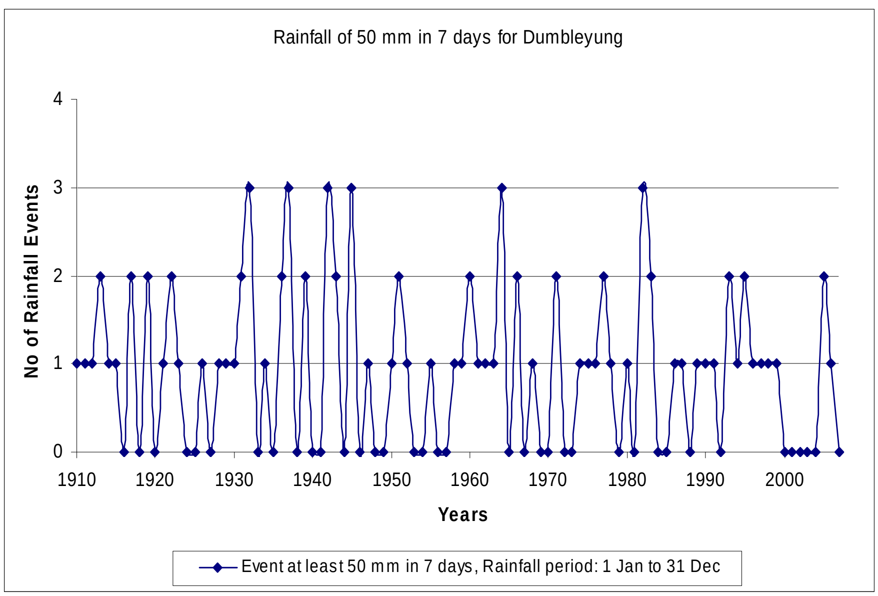


Figure 2-12 The rainfall events of 50 mm in seven days duration from 1910 to 2007 for Dumbleyung

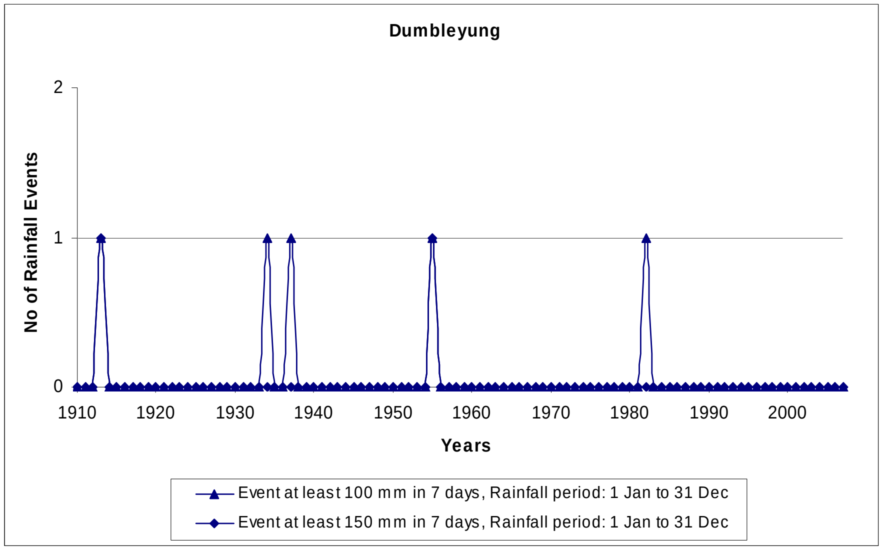


Figure 2-13 The rainfall events of 100 mm in seven days duration from 1910 to 2007 for Dumbleyung

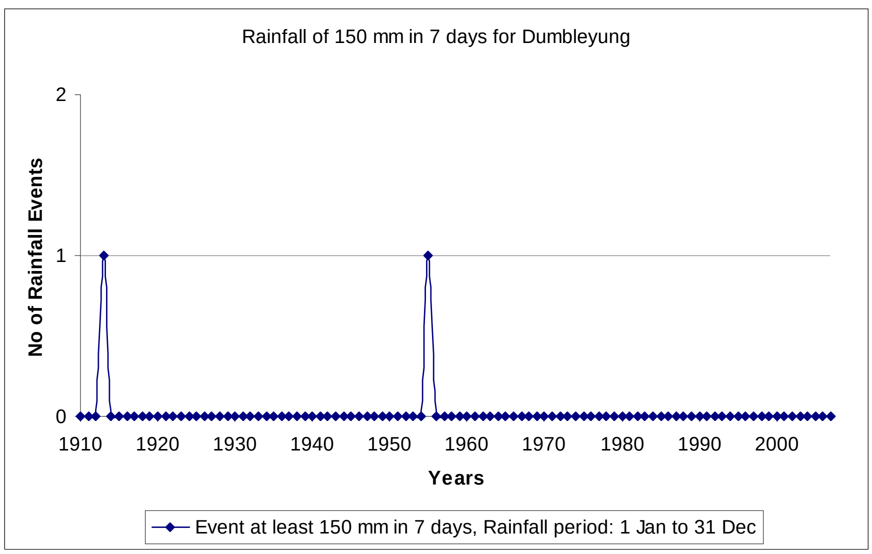


Figure 2-14 The rainfall events of 150 mm in seven days duration from 1910 to 2007 for Dumbleyung

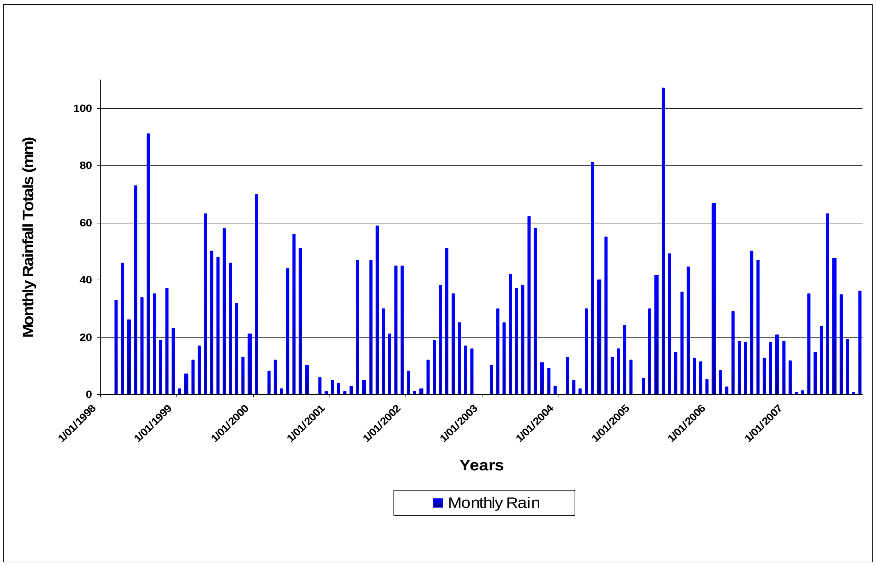


Figure 2-15 The monthly rainfall totals for Dumbleyung from 1998 to 2008.

Mean annual pan evaporation in Narembeen is 2,423 mm and in Dumbleyung 1,884 mm. Mean annual rainfall in Narembeen is about 14% of the mean annual pan evaporation and 20% in Dumbleyung. A comparison of ratio of mean annual rainfall with the mean annual pan evaporation in the Wheatbelt districts of Narembeen 14% and Dumbleyung 20% compared with the Coastal districts ratios 60% in Bunbury and 67% in Albany shows that there are more chances of groundwater recharge and stream flows in the Coastal districts. Monthly evapotranspiration (ETo) were calculated using Penman-Monteith equation for Dumbleyung and Narembeen. There was an average of 5.6 mm day^{-1} ETo for Narembeen and 4.96 mm day^{-1} ETo for Dumbleyung (Appendix 2-1).

It is generally observed that the extreme rainfall events often result in surface runoff and groundwater recharge. The rainfall events of 50 mm and 100 mm over seven days saturate the soil profile and result in significant aquifer recharge. Smaller or more sporadic rainfalls are mostly lost to evapotranspiration and surface runoff and contribute little to aquifer recharge.

About 20% of average annual rainfall is received in the summer months when the potential evaporation is high from 6 to 9 mm day^{-1}. Low rainfall in summer is unable to leach and transport the salts. Mean monthly rainfall in winter months from May to August generally exceeds evaporation. Water use of annual crops and pastures is lowest when the rainfall is highest. The low water use of the plants means that rainfall can infiltrate quickly past the plants root zone to recharge the watertable. By the time plants are into maximum water use between September and November, the majority of recharge has already occurred. Restricted drainage is a factor that usually contributes to the salinisation of soils and may involve the presence of a high ground-water table or low permeability of the soil.

2.2.3 Narembeen Zone

Between 2000 and 2003, CSIRO researchers evaluated the quantity and quality of discharge from deep, open drains at five sites within the Wakeman sub-catchment, near Narembeen, WA where about 100 kilometres of drains have been constructed since 1998 (Figure 2-16).

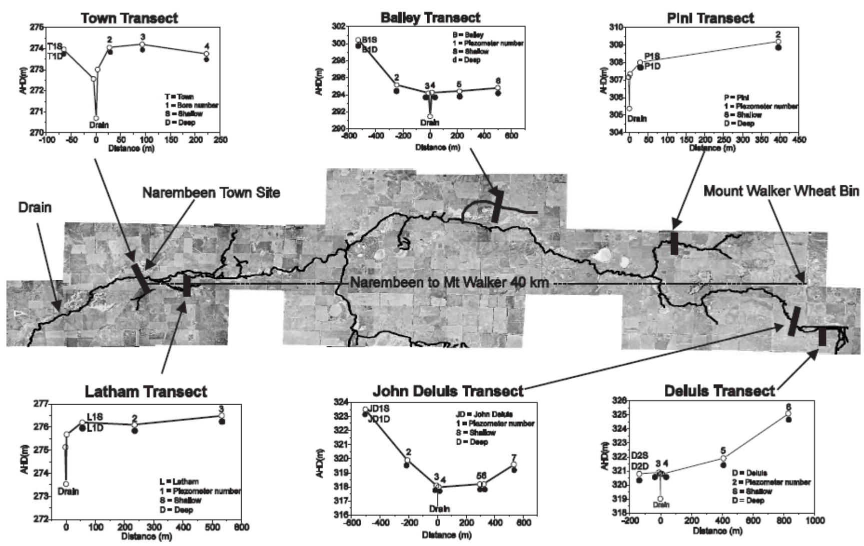


Figure 2-16 Layout of deep open drains with transects of monitoring piezometers (Ali, R. *et.al*, 2004).

During the first two years of monitoring, the flow rate in the drains was high and varied from 5-15 ML day^{-1}, which resulted in 300–600 tonnes of salt being carried away each day. There were five rainfall events of 25 mm or greater and one rainfall event of 50 mm or greater in seven days duration in 2003 which caused the groundwater recharge (Figures 2-5 and 2-6). The study found that the effect of drains on the groundwater levels was particularly significant if the initial water levels were well above the drain bed level, permeable materials were encountered, and drain depth was adequate (2-3 m). Visual observations and evidence derived from this study area suggested that if the drain depth cut through more permeable, macroporedominated siliceous and ferruginous hardpans, which exist 1.5-3 m from the soil surface, its efficiency exceeded that predicted by simple drainage theory based on bulk soil texture (Ali *et al*., 2004). URS (2005) suggested that it is possible that much of the 'influence' measured is actually due to a period of dry years that has allowed the profile to drain. There were no control data to provide a baseline to compare against the impact of the treatments. The effect of drains often extended to distances away (>200 m) from the drain. Immediately following construction, drains had a high discharge rate until a new hydrologic equilibrium was reached. After equilibrium, flow largely comprised regional groundwater discharge and was supplemented by quick responses driven by rainfall recharge (Ali *et al*., 2004). The drain may not be having an effect on groundwater levels at great distance from the drain, it could still be effective in preventing waterlogging over a large area and hence enhancing productivity over this larger area (Ali and Coles, 2000). The baseflow (dry season) fluxes in the drains, of the order of some 5-10 ML per day from a drainage system of some 70 km in length, was clearly groundwater discharge. This study clearly showed the effects of deep open drains (>2 m) on both the shallow and deep groundwater levels in the Wakeman subcatchment. Minimum groundwater levels in undrained areas in the Wakeman subcatchment were 1-1.5 m shallower than levels associated with drainage (Ali *et al*., 2004).

The outflow rate decreased substantially toward the end of 2002 due to dry weather but increased again following above average rainfall during winter 2003. The salinity and pH of the drain water varied between an electrical conductivity of 4,000–10,000 ms m^{-1} and a pH of 2–4. Apart from natural fluctuations caused by rainfall, no significant change in drain water salinity or pH was detected during four years of monitoring.

The salinity of the shallow groundwater at various sites was generally lower than that of the deep groundwater but pH values were similar. Excessive levels of manganese, aluminium and iron were detected in the drain water and potentially, if left untreated, could be harmful for downstream flora and fauna (http://hesapeakebay.net/pubs/waterqualitycriteria/doc- Ag_BMP_Defns.pdf).

The studies reviewed evaluated the on-site impacts of a deep open drains in Narembeen and on groundwater levels (Ali *et al*., 2004a) and soil salinity (Ali *et al*., 2004b). The discharge from drainage was highly acidic and saline, especially during summer when there was low discharge, and carried heavy metals at significant concentration levels (Ali *et al*, 2004c).

2.2.4 Dumbleyung Zone

Two studies have been undertaken in the Zone with the aim of determining the impact of drainage on vegetation biomass production adjacent to a drain. In the first study (Tetlow, 2001), biomass production was measured on transects 100 m long located perpendicular to and on both sides of drains constructed on two properties 11 km north of Dumbleyung. Crops were barley and Canola at one site and wheat and barley at another. Measurements of biomass were taken just before harvest in 2000 and 2001. The results of this study showed that the drain was yet to demonstrate any significant effect on biomass within a 100 m distance of the drain. The result was explained as being due to limited salinity impact on ‘pre-drain’ crop production prior to drainage, dry growing seasons without waterlogging and a too short a period after drain construction for effects to be seen. Another set of measurements taken in December 2002 showed some marginal benefits in biomass production close to the drain. There were no trends in salinity measurements using EM38 that could be explained by the drain, although watertable depths in deep and shallow bores were lower up to 30 m either side of the drain (Siddiqi, 2002).

2. 3 **Deep Drainage Study Beynon Road, Dumbleyung**

Cereal crops such as wheat and barley are the current dominant land use in Dumbleyung. The property at Beynon Road where deep open drains are installed was regularly grazed until 1996. Because of salinity grazing has only been opportunistic since 1996 (Cox, 2002). Saltbush and tree planting have been undertaken in recent years.

The soil profile of the Dumbleyung site is characteristic of the Beynon Soil Series, as described by Percy (2000). It consists of a thin layer of dark grey sandy topsoil with an abrupt boundary to clay subsoil. This subsoil becomes heavier with depth. It is usually poorly drained and often slightly salt affected. Bedrock of weathered granite is located at a depth of 4 to 6 m (Cox, 2002).

Cox (2002) used a K_{sat} value of 0.25 m d^{-1} and excavation to depths of 2 and 3 metres for designing the drainage network. The drain, berms and shaped spoils banks occupy between 13 and 20 m. The minimum acceptable depth to the watertable was set at 0.6 m. The expected performance was that the 3 m drains would control the watertable to a lateral distance of 103 m either side of the drain, and 2 metre drains would control the watertable to 86 m on either side. The area to be treated was 75 ha.

Sufficient observations have been made at the Beynon Road site to provide some empirical data on the effectiveness of drains and the issues involved in management (Anon, 2004). The scheme has discharged about 20,000 m^3 of saline and acidic water over a 12 month period, or 267 m^3 per ha treated. Additional salt export has been 1,100 tonnes. Crop productivity on salt affected land prior to drain construction was 0.5 t ha^{-1} barley. After drain construction, the landholder advises that barley yield has increased to 2.65 t ha^{-1}. Groundwater levels have dropped by 1 m up to 200 m away from the drains, although this observation needs to be investigated more thoroughly. Groundwater levels rose approximately 20 cm over winter in the drained area and dropped again over summer. Vegetation recovery within the area affected by the drainage network is reported by local observers to be rapid.

The highly acidic water discharged from the drains is being neutralised by the buffering activity of the receiving environment, being an adjacent creek which flows out of the Doradine Catchment into the Dumbleyung catchment. Indeed, this caution could extend to the interpretation of all drainage observations in the last two to three years. In all locations, it is recommended that a lengthy period of observation and measurement across a range of seasonal conditions will be needed to determine drainage effectiveness.

Groundwater levels at the Dumbleyung site prior to installation of the deep drain fluctuated between 0.70 and 1.1 m from the surface. Groundwater levels were obtained from shallow bores during March/April in 2002 using hand-held plopper. The drains were installed in December 2003. It was 4,354 m long and ranged from 3 to 1.62 m deep. It consisted of a collector drain, running approximately north-west, and four lateral drains branching to the west. The drain discharged into Dorodine Creek, a tributary of Lake Dumbleyung.

Groundwater levels data have been downloaded from Department of Water, Perth website. The data is in graphical format and maximum and minimum groundwater levels in each year before installation of drains in 2002 and after constructions of drains until 2005 was available. Highest and lowest groundwater level of each year has been worked out of all monitoring bores and groundwater drawdown and recovery of each year has been calculated (Appendix 2-2). A high resolution Google imagery of Beynon Road drainage site was downloaded in 2007. The imagery was rectified using ground control points in Ortho and Geocoding Wizard of ER Mapper. The layout of deep open drains and groundwater monitoring bores are presented in Figure 2-17. Eastings and northings of each monitoring bore and groundwater level data of all monitoring bores were saved in a file in Excel in debase4 format. This file was imported in ArcView GIS by making the Spatial Analyst extension active and from the Project window data Table was added that was in .dbf format. The groundwater contours were worked out in ArcView GIS by assigning Eastings to Xfield, Northings to Yfield and groundwater level data to Zfield by selecting an Event Theme from View window. Now from Surface command select Create Contours and select the data file with .dbf extension in Output grid extent window. In the Interpolate Surface, Inverse Distance Weighted (IDW) method was selected which determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. Zvalue field was again selected and Nearest Neighbours was preferred to Fixed Radius method. The number of neighbours and power can be trialled with contour intervals to get the optimum shapes of the contours.

The highest groundwater contours before the construction of deep drains in 2002 are given in Figure 2-17. Groundwater flow direction is vertical to groundwater contours towards south to south-east. Figure 2-18 shows the lowest groundwater contours in 2003 at Beynon Road in Dumbleyung. On an average groundwater level in all observation bores in 2002 was at 281.8 m AHD which declined to an average of 280.5 m AHD in 2003 an average drawdown of 1.2 m in groundwater level (Appendix 2-2). Highest groundwater levels observed in 2003 after winter rainfall recharge at Beynon Road in Dumbleyung resulted in groundwater level recovery of 0.6 m (Figure 2-19). The lowest groundwater level was observed in 2004 with an average groundwater level of 280.3 m AHD and an average recovery of 0.5 m. Groundwater level rose in 2005 after recharge from rainfall infiltration. The groundwater contours of 2005 have been presented in Figure 2-20. During 2005, the average groundwater level rose to 281.2 m AHD. The maximum drawdown of 1.7 m and a minimum drawdown of 1.3 m occurred in monitoring bores DD1-DD4 in the north-east corner close to collector drain and in monitoring bores from DD25 to DD31 in between lateral drains where perched groundwater is visible in the satellite imagery.

Seasonal fluctuations occur in the groundwater levels in the lower reaches of the catchment, water level rise during winter and fall during summer in response to rainfall fluctuations. If 30 mm annual groundwater recharge is considered (Chapter 5) for shallow sandy duplex soil a specific yield of 0.05 can explain a recovery of 0.6 m in 2003. In the year 2004 a 25 mm of groundwater recharge will result in a specific yield of 0.05.

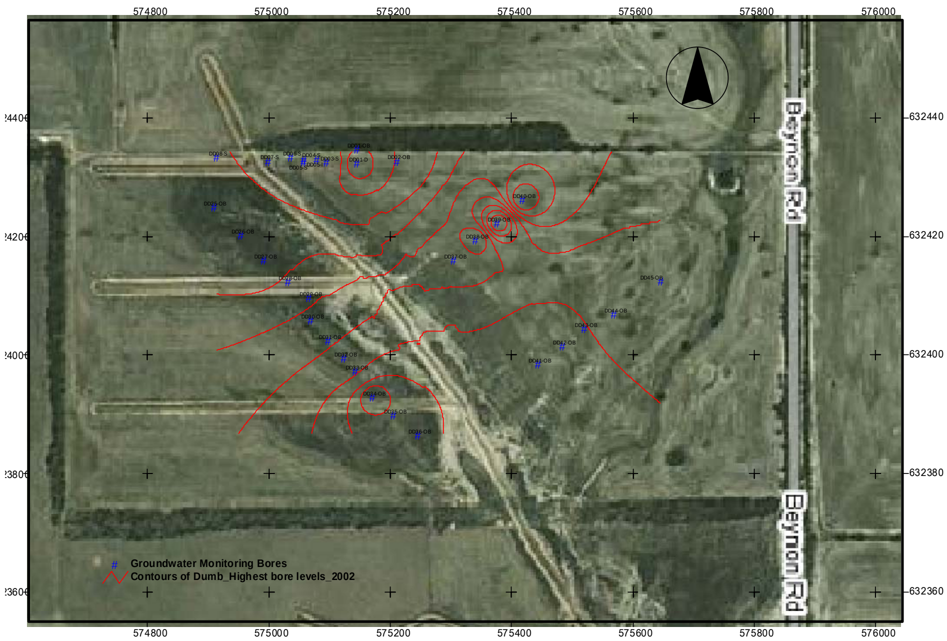


Figure 2-17 Highest groundwater contours in 2002 before construction of deep drains at Beynon Road in Dumbleyung

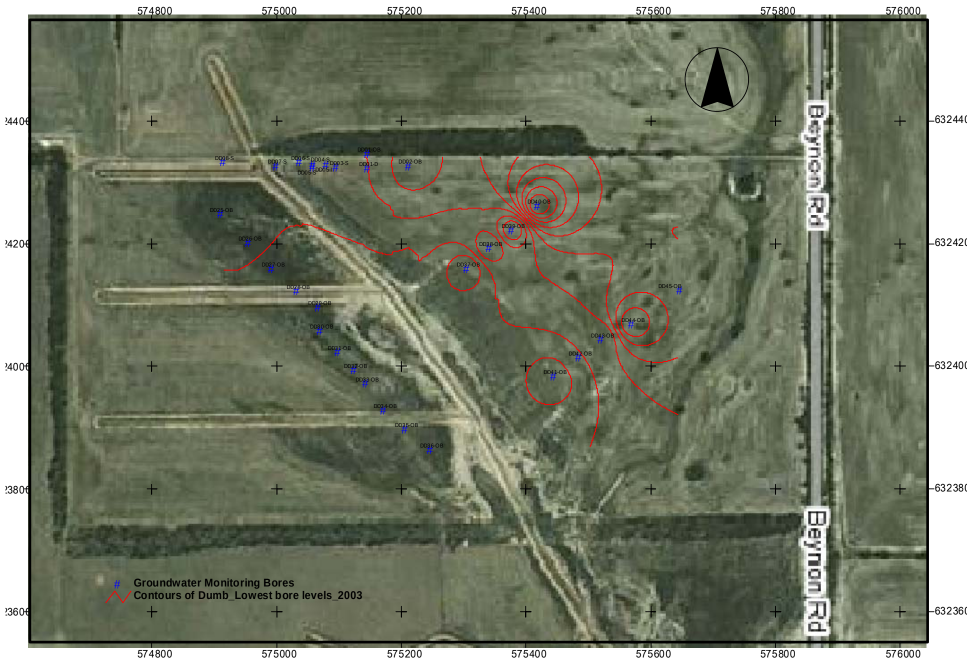


Figure 2-18 Lowest groundwater levels in 2003 at Beynon Road in Dumbleyung

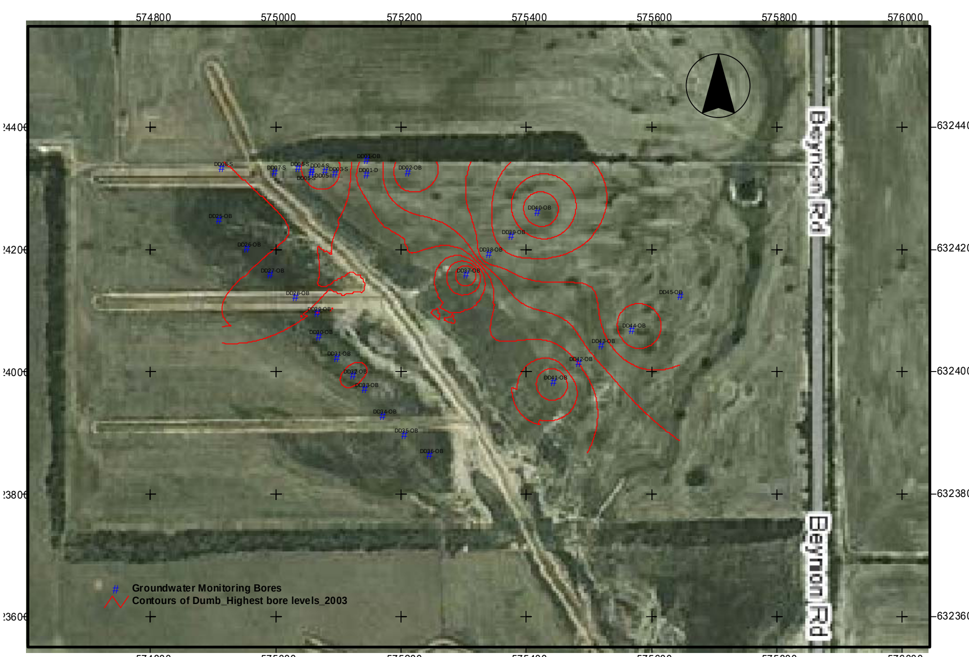


Figure 2-19 Highest groundwater levels in 2003 after winter rainfall recharge at Beynon Road in Dumbleyung

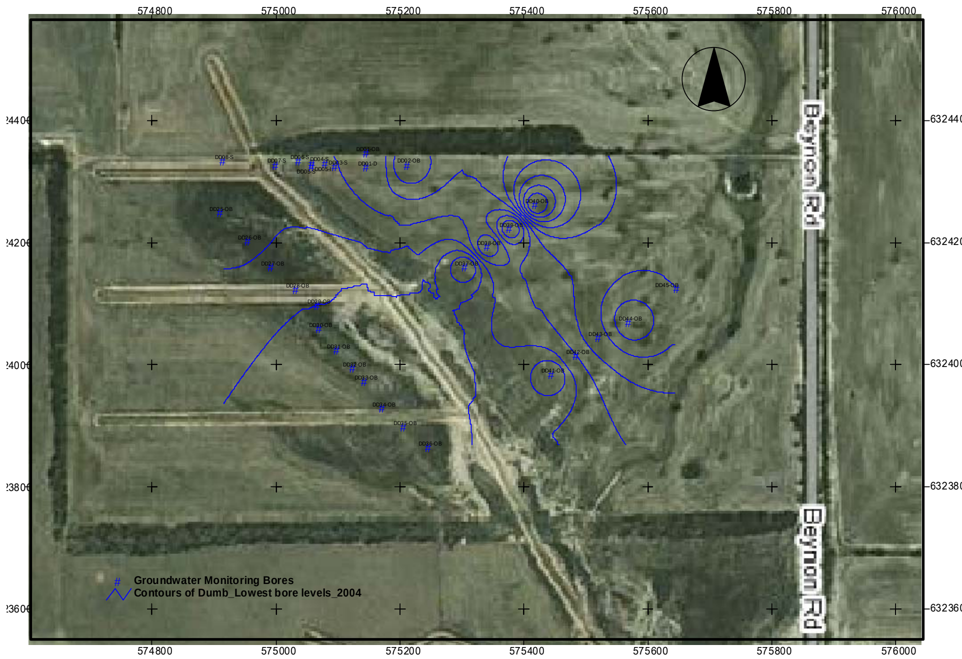


Figure 2-20 The lowest groundwater levels in 2004 after construction of drains in December, 2003 at Beynon Road in Dumbleyung

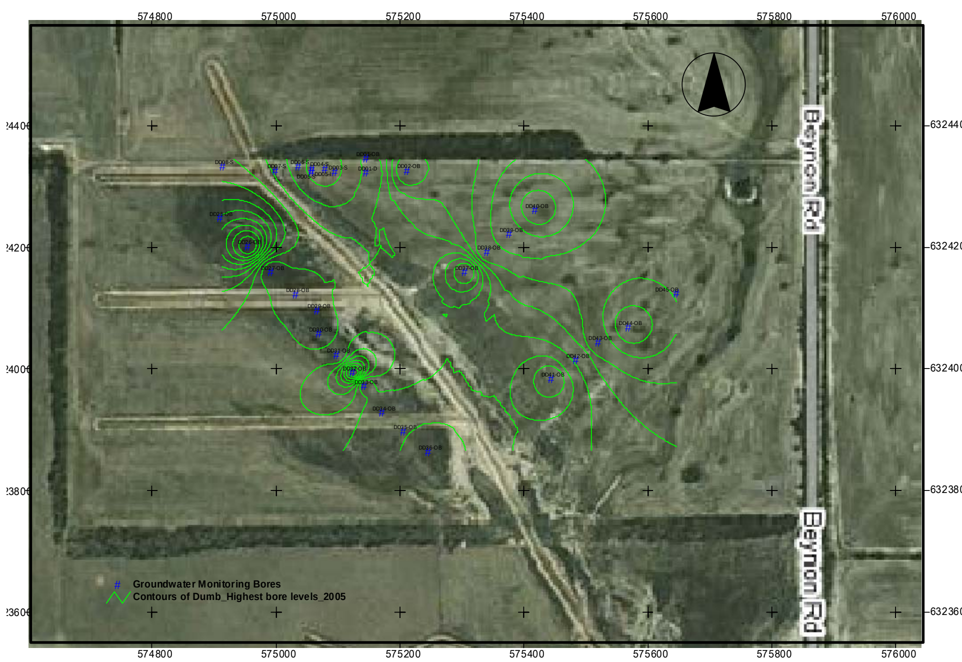


Figure 2-21 Highest groundwater levels in 2005 after recharge from rainfall at Beynon Road in Dumbleyung

2. 4 **Results and Discussions**

The problems of waterlogging and soil salinisation develop when the water levels rise relatively close to the soil surface. The salinity risk to crop growth depends on quality of the water table. Chaudhary *et al*., (1974) quantified the crop response to depth and salinity of groundwater. They found that for optimum crop production high salinity water table depth should be maintained below 2 m from surface of soil. The salinity of the groundwater is high in Dumbleyung (more than 2,000 mS m^{-1}) and if water level is below 2 m depth from the soil surface, soil salinity will develop because crops will use that water to meet their crop water requirements and salts will get accumulated in the root zone.

Long-term monitoring of deep drains at Beynon Road, Dumbleyung from 2002 to 2005 in managing depth of groundwater table suggests that drains significantly decreased groundwater level and it will have good impact on crop production. The watertable depth was within 2 m of depth from surface of soil in 2002 considering an average elevation of 283.5 m AHD of the study area (Figure 2-22). The watertable depth fell below 2 m depth from surface of soil in 2004 in all monitoring bores (Figure 2-23).

Groundwater level of two other deep drainage sites in Dumbleyung show the similar drawdown and recovery pattern from 2002 to 2005. The monitoring of groundwater level started two years after the construction of deep open drains at Temby Road and Mount Pleasant Road sites (Appendix 2-3 and Appendix 2-4). The average drawdown of three monitoring bores at Temby Road was 0.5 m and an average drawdown of four monitoring bores was 0.2 m at Mount Pleasant Road in 2003. There was an average initial groundwater drawdown of 1.2 m in 2003 as shown in Appendix 2-2. The lowest groundwater level was observed in 2004 at three groundwater monitoring sites.

Initial investigations of some major drainage schemes have found that these can discharge waters of pH 2-3 with a salinity of 30,000 to 50,000 mg L^{-1} at 5-10 ML per day (Ali *et al*., 2004b). Drainage water disposal with high salinity, high acidity and heavy metals is one of the major problems associated with deep drains and future research is required to develop practical and environmentally acceptable options for its management and disposal.

There are problems associated with deep drainage of sodic and acidic soils. Drainage water is highly saline, acidic and contains heavy metals and other nutrients as chemical fertlisers. The drains can exacerbate flooding in a region. Poorly designed and constructed drainage schemes can have significant negative on-site and off-site effects. This result in land degradation in the form of erosion from poorly constructed drains, increased risk of salinity and waterlogging downstream, sedimentation of natural streams and rivers and agricultural chemicals in water discharges leading to the loss of native plants. Subsurface drainage through pipes is not practised in the Wheatbelt because of problem of iron precipitates in drain lines.

The Department of Agriculture and Food, the Department of Water and other agencies have undertaken research into deep drainage and published Bulletins, Farm Notes, Fact Sheets and reports that provide some guidance for designing and planning the drainage in the Wheatbelt. Depth to watertable, seepage rate into drain and road crossings are additional parameters to be considered for the designing and planning of drainage system. An arterial deep drainage design can play within an overall water management strategy for integrating scattered drainage systems with neighbouring properties and regional systems. Safe disposal of drainage water and other effluents into evaporation basins, lakes and streams should be the part of drainage planning. Drainage planning and designing of deep open and double leveed drains in duplex, saline and sodic soils in different catchment areas, slopes, length of main stream lines should be done using techniques and modelling of flow accumulation and digital elevation models discussed in the fourth chapter.

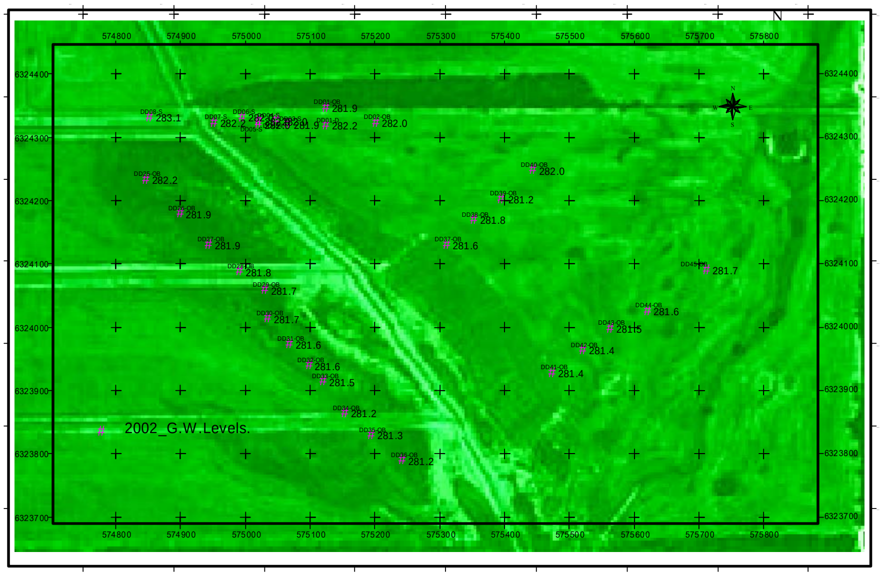


Figure 2-22 Highest groundwater levels in 2002 before construction of deep drains at Beynon Road in Dumbleyung

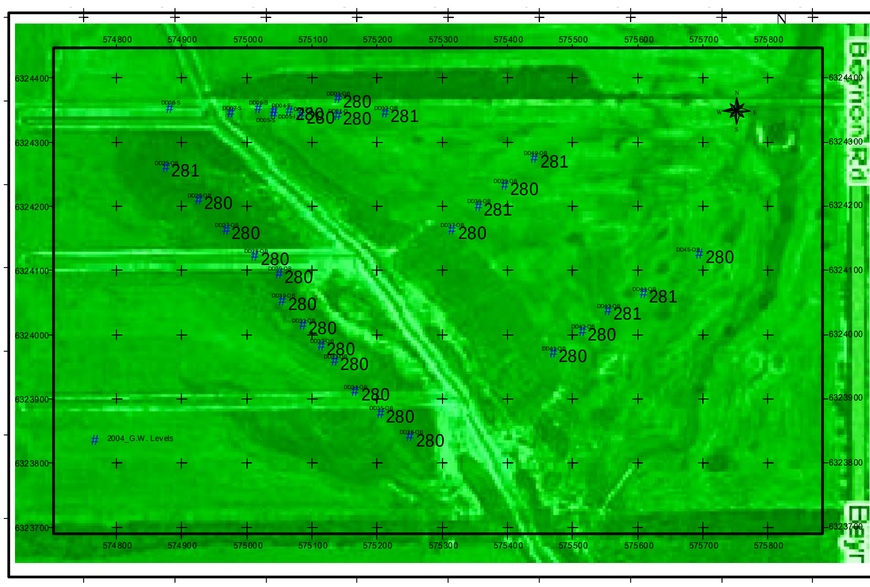


Figure 2-23 Lowest groundwater levels in 2004 at Beynon Road in Dumbleyung

3 USE OF REMOTE SENSING IN MONITORING DEEP DRAINS OF WHEATBELT, WESTERN AUSTRALIA

3. 1 Literature Review

Literature review of research done to identify and map the saline and waterlogged areas in Australia and abroad is presented in the following sections.

Wheaton *et al*., (1994) developed a method to map salt affected agricultural land by assessing landcover from multiple date Landsat TM images by separating salt-affected groundcover types from cropped land and remnant vegetation. Terrain analysis improved the accuracy of salinity mapping by identifying areas most likely to be affected by rising groundwater (broad valleys). Salama *et al*., (1996) also recognized the importance of terrain analysis and landscape features in forecasting the development of groundwater systems and the process of salinisation and approached the problem from a hydrogeological perspective.

Metternicht and Zinck (1996) used a synergistic approach to map salt and sodium affected surfaces, combining digital image classification with field observation of soil degradation features and laboratory determinations. Salinity-alkalinity classes were established using the electrical conductivity (EC) and pH values. A neighbourhood operator, with spatial and spectral user-defined constraints determined the spectral objects constituting the training set. Six combined Landsat TM bands (1,2,4,5,6,7) provided the highest separability between salt- and sodium-affected soil classes. They used laboratory determinations of Csillag et al. (1993) who found six spectral ranges characterising the salinity status of soils undergoing different salinisation and alkalinisation processes. These key bands were in the visible (0.55± 0.77 μm), near-infrared (0.9± 1.3 μm), and middle-infrared (1.94± 2.15 μm; 2.15± 2.3 μm; 2.33± 2.4 μm). Aerial photos have been used in soil salinity mapping, especially colour-infrared photographs in which barren saline soils (in white) and salt-stressed crops (in reddish brown) can be easily discriminated from other soil surface and vegetation features Rao and Venkataratnam (1991); Wiegand *et al*., (1994). Metternicht and Zinck (2003) provided a review on satellite imagery covering the visible to infrared regions of the spectrum for identification and mapping of saline areas. The reflectance increases with increasing quantity of salts on the soil surface. Salt-affected soils show relatively higher spectral response in the visible and near-infrared regions of the spectrum than non-saline soils do, and strongly saline-sodic soils present higher spectral response than moderately saline-sodic soils (Rao *et al*., 1995).

Taylor and Dehaan (2000) used Hymap airborne sensor that acquires hyperspectral images over the spectral range of 450–2,500 nm (i.e. visible, near- and mid-infrared) in 128 bands, to map saline areas characterised by salt scalds, halophytic vegetation, and soils with varying salinity degrees and types. Using spectral unmixing, they found that saline endmembers presented a pronounced high reflectance at 800 nm, a shallow and wide hydroxyl feature at 2,200 nm, and broad absorption features at 1450 and 1,900 nm. Ben-Dor *et al*., (2002) reported successful results in using the hyperspectral DAIS-7915 sensor and the Visible and Near-Infrared Analysis (VNIRA) approach to produce quantitative soil surface maps of organic matter, soil field moisture, and soil salinity. Dwivedi and Sreenivas (1998) have delineated salt-affected soils and waterlogged areas in the Indo-Gangetic irrigated plains and showed that the spectral response pattern of salt-affected soils is relatively higher than other two categories, namely waterlogged areas and crop lands, in the three bands, except for near infrared, where the vegetation reflects the maximum.

The Land Monitor Project, a project of the WA Australian Salinity Action Plan supported by the Natural Heritage Trust, has mapped areas of shallow watertable and salinity risk and reports of fifteen districts in wheatbelt have been posted on their website (http://www.landmonitor.wa.gov.au/). Salinity map was produced by combining Landsat TM data; e.g. 1988-96 data for Kellerberrin, and information derived from digital elevation models. The data were extracted from the satellite imageries in August and September and those areas were mapped as salt-affected, that had persistent low productivity for more than two seasons but it may include salt-affected land, dry dams, dam embankments, fire breaks and roads. The precise definition of salt-affected is dependent in part on the qualitative assessment of the ground-truthing personnel and in part on the limitations of the productivity changes that can be reliably measured by the Landsat TM instrument. After combining the cover class probabilities from each date with position in the landscape i.e. hill, slope and valley floor probabilities were calculated for each pixel being salt-affected. A conditional probability network was used to get five classes of Nonsaline, Mapped as saline in 1989, Mapped as saline in 1995, Dark vegetation (includes remnant vegetation, wet scrub and reeds) and Wet Class (Caccetta, 1997). Caccetta (1997) cautioned for the interpretation of the prediction results as to a large degree, predictions relied heavily on the landform variables derived from the DEM and therefore are partially bound by the errors in landform partitioning. Land Monitor does not consider the affect of geology and vegetation in its modelling. Some research in WA has been done to monitor and delineate areas of risks of salinity and waterlogging on regional scale with little validations of results as ground truth data collection is difficult on regional scale. There are social issues involved in declaring an area salt-affected as the prices of land will fall. Disposal of water from drainage and pumping schemes from a property may impact downstream neighbouring properties and salanise the streams and rivers.

This Ph.D. study will examine change in vegetation; identify saline and waterlogged areas in two drainage districts in WA using high resolution satellite. The remote sensing techniques to identify and map salinity, waterlogging and drought areas in WA will be useful to accurately predict their impacts in an area and effects on crop and pastures growth. The WA government agencies may take necessary action if there are negative on-site, off-site and downstream ecological and hydrological impacts of discharge of drainage water. Results from drought study can be used for prompt decision-making processes like declaration of exceptional circumstances and drought in an area. The remote sensing and GIS models developed during the Ph.D. study will offer time and cost effective methods of temporal monitoring of land degradation in an area.

3. 2 **Salinity and Waterlogging**

Excess water in the landscape can be managed using engineering interventions such as deep drains and groundwater pumping. Both drainage and pumping can improve the outflow of water from both the saturated and unsaturated soil zones and reduce periodic seasonal events such as waterlogging and inundation. Groundwater pumping and deep open groundwater drains are used to reduce land salinisation at scales from managing local discharges to regional systems (Otto and Salama, 1994; Ali and Coles, 2001). Hatton (1999) recognised that engineering can be effective in reducing the impacts and extent of land salinisation on infrastructure and natural assets, as well as in keeping land under crops. Salama *et al.,* (1999) used HARSD in combination with Flownet to estimate the changes in salinity risk associated with large-scale reforestation in south-eastern Australia.

However, poorly designed and constructed drainage and pumping schemes can have significant negative on-site and off-site effects. This result in land degradation in the form of erosion from poorly constructed drains, increased risk of salinity and waterlogging downstream, sedimentation of natural streams and rivers and agricultural chemicals in water discharges leading to the loss of native plants. In the last 10 years, engineering interventions have increasingly been seen as a viable option to combat dryland salinity in the Wheatbelt of WA. Drains now exist in almost every catchment of the Wheatbelt. The total length of these drains now exceeds 12,000 km but almost all of them have been constructed without any formal evaluation of their impacts on hydrology and ecology of the downstream rivers and streams that receive the drainage discharge from these drains. Currently most drains discharge into local creeks or salt lakes or even at the farm fence. Initial results show that the drains discharge hyper-saline groundwater that is also highly acidic (pH <3) into streams with significant amounts of heavy metals. If ecological and hydrological impacts of engineering interventions of deep drains and groundwater pumping are to be modelled and monitored on catchment and sub-catchment scale, field surveys for information collection will not be feasible and remote sensing techniques may prove a useful alternative.

Wheaton *et al*., (1994) developed a method to map salt affected agricultural land by assessing landcover from multiple date Landsat TM images by separating salt-affected groundcover types from cropped land and remnant vegetation. Terrain analysis improved the accuracy of salinity mapping by identifying areas most likely to be affected by rising groundwater (broad valleys). Salama *et al*., (1996) also recognized the importance of terrain analysis and landscape features in forecasting the development of groundwater systems and the process of salinisation and approached the problem from a hydrogeological perspective.

Metternicht and Zinck (1996) used a synergistic approach to map salt and sodium affected surfaces, combining digital image classification with field observation of soil degradation features and laboratory determinations. Salinity-alkalinity classes were established using the electrical conductivity (EC) and pH values. A neighbourhood operator, with spatial and spectral user-defined constraints determined the spectral objects constituting the training set. Six combined Landsat TM bands (1,2,4,5,6, and 7) provided the highest separability between salt- and sodium-affected soil classes. They used laboratory determinations of

Csillag et al. (1993) who found six spectral ranges characterising the salinity status of soils undergoing different salinisation and alkalinisation processes. These key bands were in the visible (0.55± 0.77 µm), near-infrared (0.9± 1.3 µm), and middle-infrared (1.94± 2.15 µm; 2.15± 2.3 µm; 2.33± 2.4 µm). Aerial photos have been used in soil salinity mapping, especially colour-infrared photographs in which barren saline soils (in white) and salt-stressed crops (in reddish brown) can be easily discriminated from other soil surface and vegetation features Rao and Venkataratnam (1991); Wiegand *et al*., (1994). Metternicht and Zinck (2003) provided a review on satellite imagery covering the visible to infrared regions of the spectrum for identification and mapping of saline areas. The reflectance increases with increasing quantity of salts on the soil surface. Salt-affected soils show relatively higher spectral response in the visible and near-infrared regions of the spectrum than non-saline soils do, and strongly saline-sodic soils present higher spectral response than moderately saline-sodic soils (Rao et al., 1995).

Taylor and Dehaan (2000) used Hymap airborne sensor that acquires hyperspectral images over the spectral range of 450–2,500 nm (i.e. visible, near- and mid-infrared) in 128 bands, to map saline areas characterised by salt scalds, halophytic vegetation, and soils with varying salinity degrees and types. Using spectral unmixing, they found that saline endmembers presented a pronounced high reflectance at 800 nm, a shallow and wide hydroxyl feature at 2,200 nm, and broad absorption features at 1,450 and 1,900 nm. Ben-Dor *et al*., (2002) reported successful results in using the hyperspectral DAIS-7915 sensor and the Visible and Near-Infrared Analysis (VNIRA) approach to produce quantitative soil surface maps of organic matter, soil field moisture, and soil salinity. Dwivedi and Sreenivas (1998) have delineated salt-affected soils and waterlogged areas in the Indo-Gangetic irrigated plains and showed that the spectral response pattern of salt-affected soils is relatively higher than other two categories, namely waterlogged areas and crop lands, in the three bands, except for near infrared, where the vegetation reflects the maximum.

The Land Monitor Project, a project of the WA Australian Salinity Action Plan supported by the Natural Heritage Trust, has mapped areas of shallow watertable and salinity risk and reports of fifteen districts in wheatbelt have been posted on their web site (http://www.landmonitor.wa.gov.au/). Salinity map was produced by combining Landsat TM data; e.g. 1988-96 data for Kellerberrin, and information derived from digital elevation models. The data were extracted from the satellite imageries in August and September and those areas were mapped as salt-affected, that had persistent low productivity for more than two seasons but it may include salt-affected land, dry dams, dam embankments, fire breaks and roads. The precise definition of salt-affected is dependent in part on the qualitative assessment of the ground-truthing personnel and in part on the limitations of the productivity changes that can be reliably measured by the Landsat TM instrument. After combining the cover class probabilities from each date with position in the landscape i.e. hill, slope and valley floor probabilities were calculated for each pixel being salt-affected. A conditional probability network was used to get five classes of Nonsaline, Mapped as saline in 1989, Mapped as saline in 1995, Dark vegetation (includes remnant vegetation, wet scrub and reeds) and Wet Class (Caccetta, 1997). Caccetta (1997) cautioned for the interpretation of the prediction results as to a large degree, predictions relied heavily on the landform variables derived from the DEM and therefore are partially bound by the errors in landform partitioning. Land Monitor does not consider the affect of geology and vegetation in its modelling.

3. 3 **Methodology of Remote Sensing Data Analysis**

Landsat Thematic Mapper (TM) imageries from 1989 to 1998 were provided by CSIRO Land Water, Perth and Landsat Enhanced Thematic Mapper (ETM+) Imageries of 2002 and Landsat TM imageries of 2004 and 2005 for Kellerberin (111-082) and Dumbleyung (111-083) that include the open deep drainage study area were purchased from Landgate, Perth. Landsat images from 1989 to 1998 were in TMAMG50 projection and AGD 1966 datum all of these images were converted to MGA50 projection and GDA94 datum to match the coordinate system of images from 2002 to 2005. The spatial resolution of 30 by 30 m has been converted to 25 by 25 m. Details of the Landsat data used in the analysis is given in the Table 3-1.

Landsat 5 TM and Landsat 7 ETM+ images acquired from 1989 to 2005 for Narembeen and Dumbleyung deep drainage sites have been used to compute the True Colour and Near Infrared composite and three spectral indices in the following sections.

Following map extents have been taken for remote sensing study of Narembeen and Dumbleyung deep drainage study sites (GDA94; AMG Zone 50). ER Mapper can be used to select the deep drainage study sites. In ER Mapper open the View window and select Geoposition and in the extents window enter the eastings and northings of top left and bottom right points of Narembeen and Dumbleyung.

Narembeen Area:

Top Left E 626483 N 6459433

Bottom Right E 647966 N 6443266

Dumbleyung Area:

Top Left E 567782 N 6325809

Bottom Right E 578976 N 6317373

Table 3-1 Details of the Landsat data

Landsat Sensor	Date of capture (satellite overpass)
TM	10 August 1989
TM	14 September 1990
TM	23 September 1993
TM	8 August1994
TM	27 August 1995
TM	29 August 1996
TM	14 September 1998
ETM+	22 August 2002
TM	3 August 2004
TM	21 July 2005

3.3.1 True Colour Composite (321)

TM and ETM+ bands 1, 2, and 3 record reflected light energy in blue, green and red bands. The blue, green and red bands (1, 2 and 3) of the TM are narrow (between 60 and 80 nm) and their spectral position is designed to measure the green vegetation peak and the chlorophyll absorption. True colour composite images are created by combining the ETM spectral bands that most closely resemble the range of vision of the human eye. Figure 3-1 shows a true-colour composite of deep drainage area near Narembeen Town, of 10 August 1989, using the visible red (band 3), visible green (band 2), and visible blue (band 1).

True colour image is showing vegetation in medium to light green, trees and bushes in olive green, water in shades of blue and green, bare soil in white to light gray and developed area in white to light gray. Blue light is easily scattered in the atmosphere which gives the low contrast and hazy appearance to the true colour composite. The presence of haze, shadows and clouds also affect the quality of the true colour image.

3.3.2 Near Infrared Composite (432)

TM and ETM+ bands 4, 5, and 7 record reflected light in wavelengths that human eyes cannot see. TM and ETM+ band 4 is referred as Near Infrared (NIR) and TM band 5 and ETM+ band 7 as Short Wave Infrared (SWIR). TM band 4 (Near Infrared) is centred in a region of maximum sensitivity to plant vigour. Sensitivity to plant water stress is obtained in both the TM mid-infrared bands (TM band 5 and 7).

Figure 3-2 shows a NIR composite of deep drainage area near Narembeen Town, of 10 August 1989, using the Near Infrared (band 4), Red (band 3), and Green (band 2).

A NIR composite shows vegetation as red instead of green because chlorophyll in leaves of vegetation reflects in the NIR band. A NIR (4, 3, 2) composite image shows vegetation in varying shades of red because different types of vegetation have different levels of chlorophyll in their leaves. A NIR composite shows crops in pink to red colour, trees and bushes in red, water in shades of blue, clear water in black, bare soil in blue to gray and developed area in blue to gray. A NIR image can be used to classify different types of vegetation. Water absorbs nearly all of the NIR energy and it appears very dark to nearly black in a NIR composite image.

A comparison of Landsat 5 TM image of 29 August 1996 for Narembeen in NIR image (Figure 3-6) representing pre-drainage image and Landsat 5 TM image of 22 August 2002 for Narembeen in NIR image (Figure 3-8) shows that cropped area has increased close to drains in the post-drainage image. A comparison of Landsat 5 TM image of 14 September 1990 for Dumbleyung in NIR image (Figure 3-14) and Landsat 5 TM image of 14 September 1998 for Dumbleyung in NIR image (Figure 3-16) shows that land degradation due to soil salinity and waterlogging has increased in the field where deep drains were installed in 2003.

Figure 3-1 Landsat 5 TM image of 10 August 1989 for Narembeen in true colour
R, G, B = TM Band 3, 2, 1

Figure 3-2 Landsat 5 TM image of 10 August 1989 for Narembeen in NIR image
NIR, R, G = TM Band 4, 3, 2

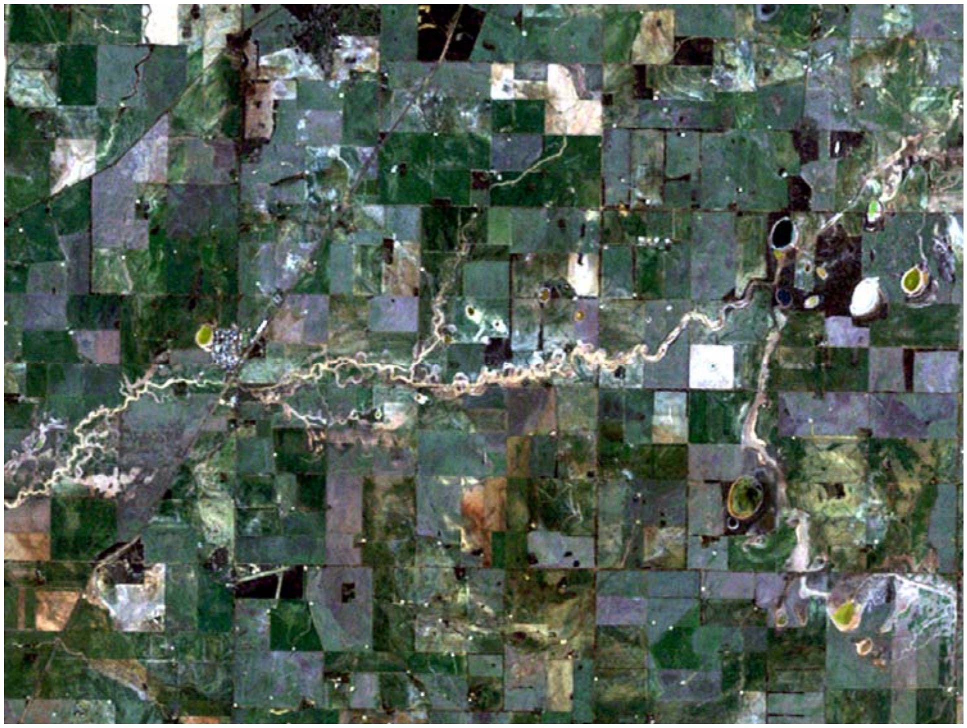


Figure 3-3 Landsat 5 TM image of 8 August 1994 for Narembeen in true colour
R, G, B = TM Band 3, 2, 1

Figure 3-4 Landsat 5 TM image of 8 August1994 for Narembeen in NIR image
NIR, R, G = TM Band 4, 3, 2

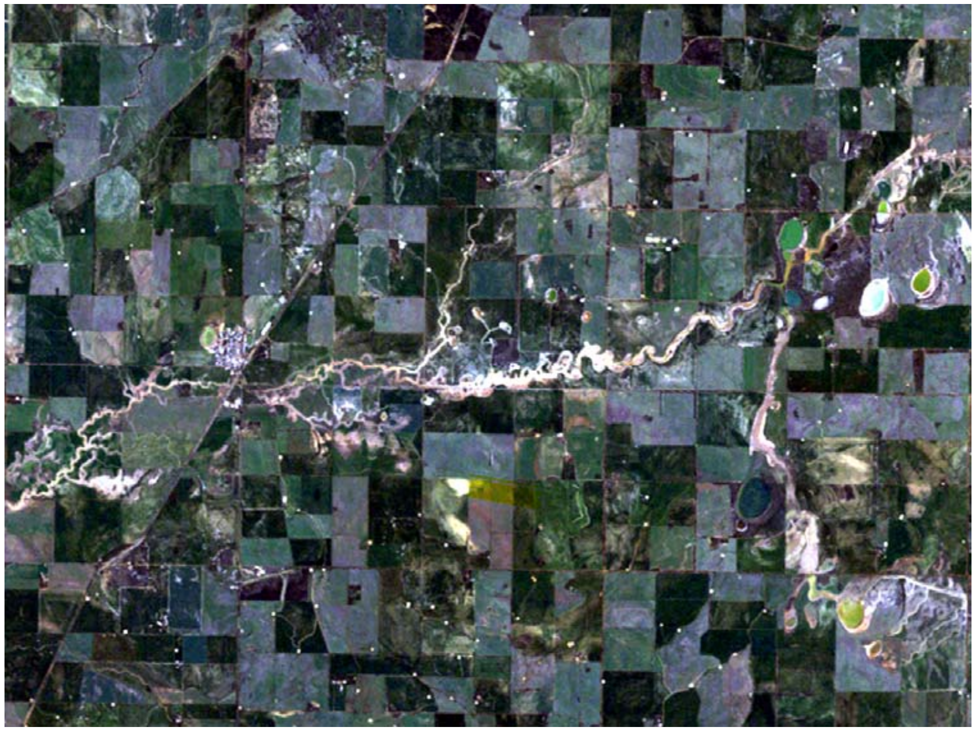


Figure 3-5 Landsat 5 TM image of 29 August 1996 for Narembeen in true colour
R, G, B = TM Band 3, 2, 1

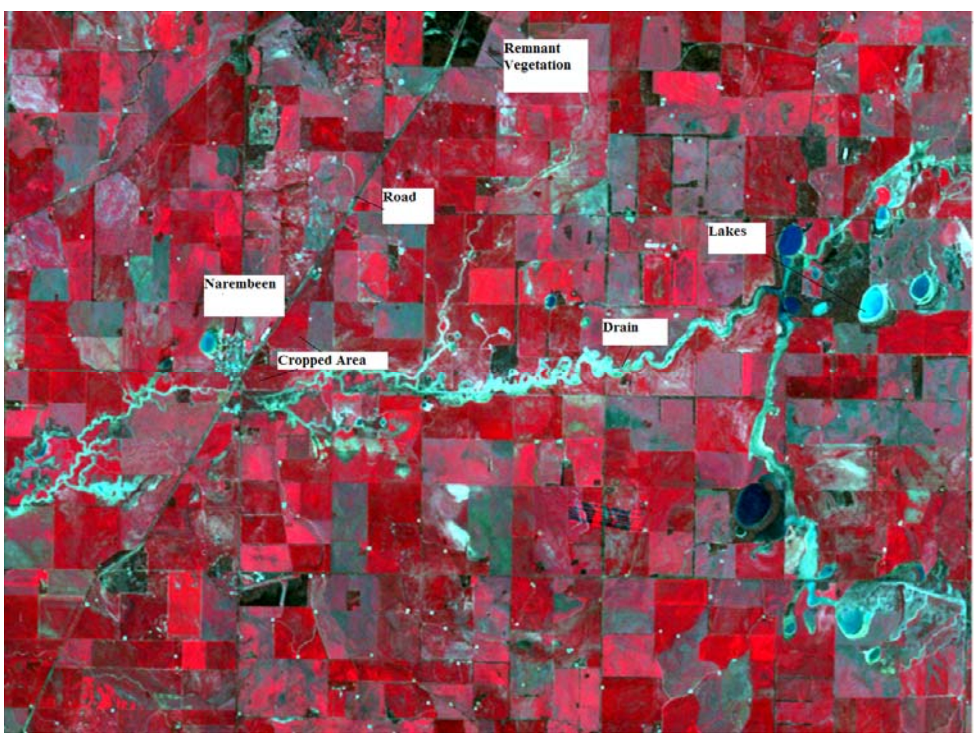


Figure 3-6 Landsat 5 TM image of 29 August 1996 for Narembeen in NIR image
NIR, R, G = TM Band 4, 3, 2

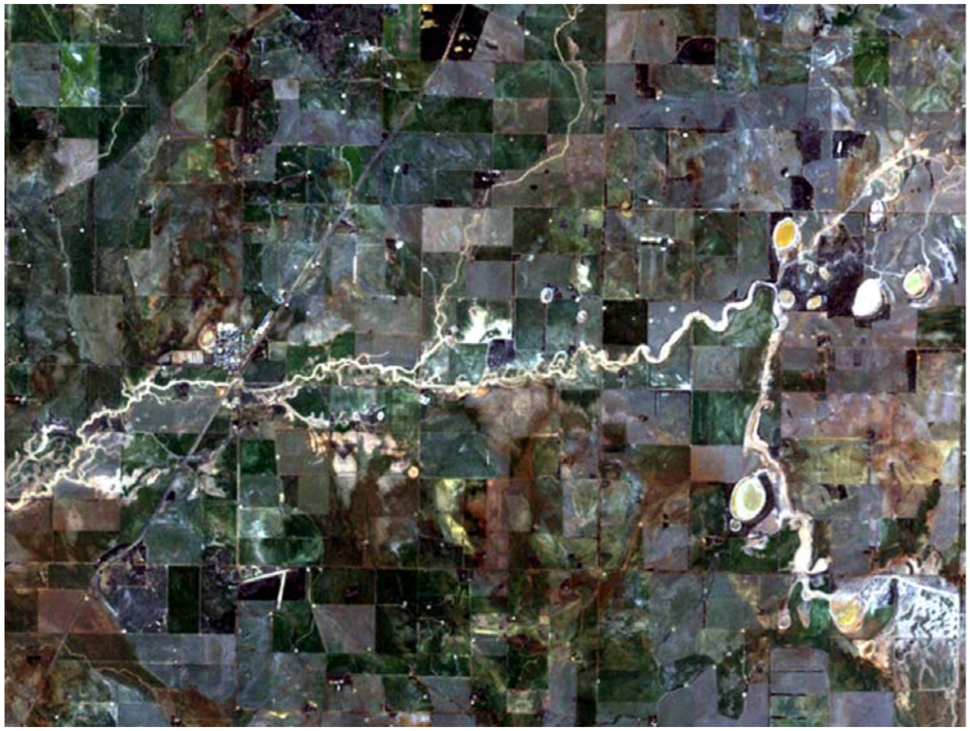


Figure 3-7 Landsat 5 TM image of 22 August 2002 for Narembeen in true colour R, G, B = TM Band 3, 2, 1

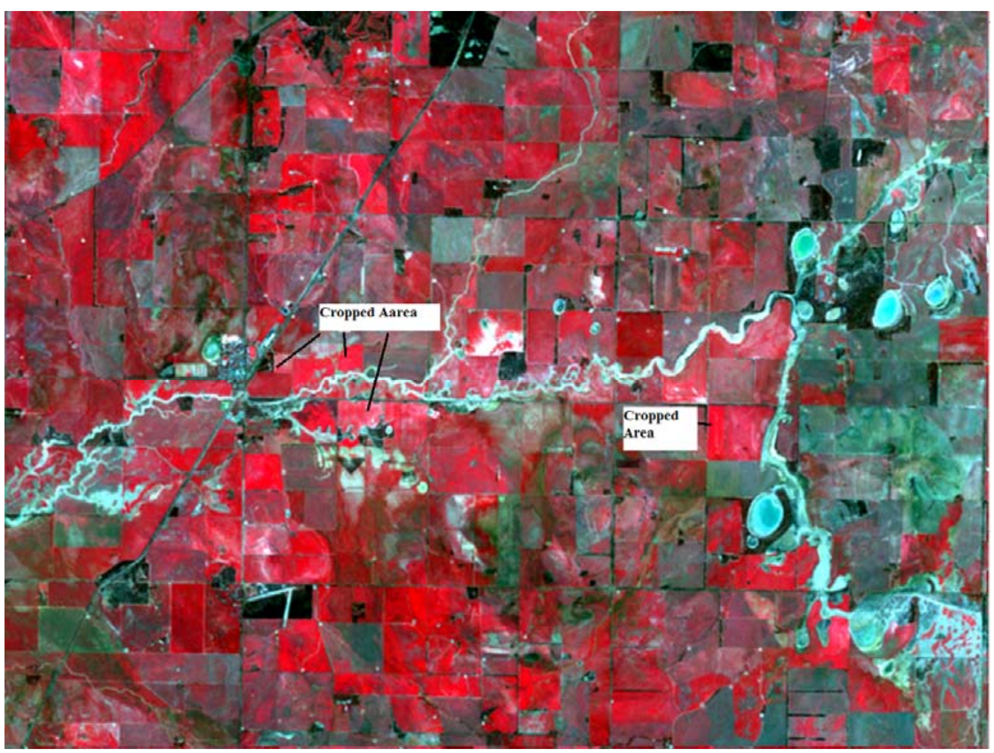


Figure 3-8 Landsat 7 ETM+ image of 22 August 2002 for Narembeen in NIR image NIR, R, G = ETM+ Band 4, 3, 2

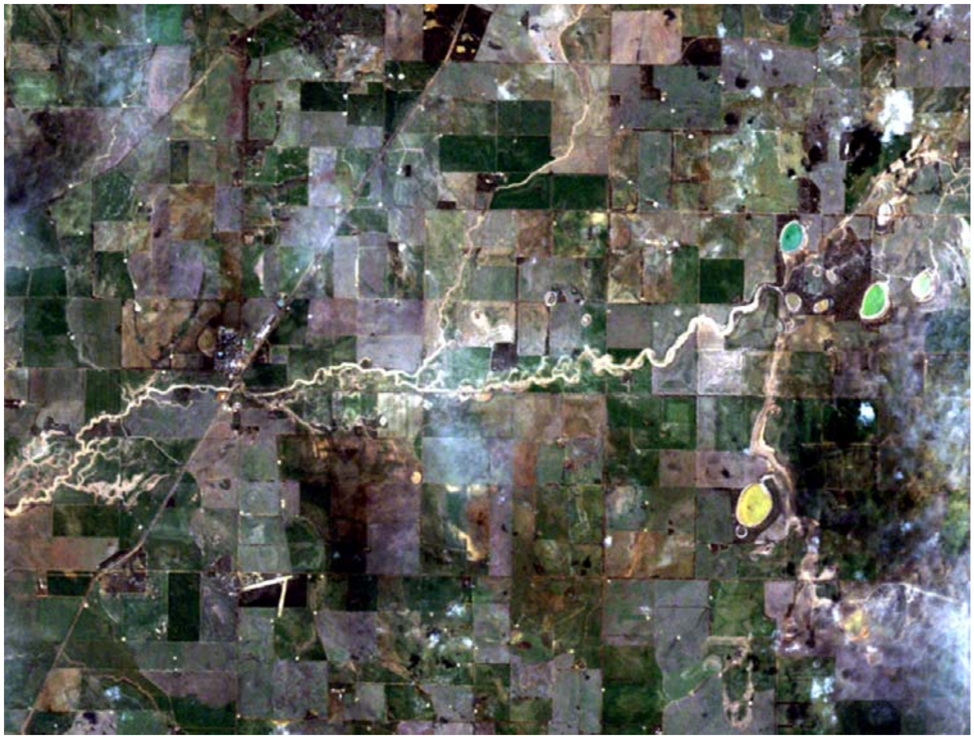


Figure 3-9 Landsat 5 TM image of 3 August 2004 for Narembeen in true colour R, G, B = TM Band 3, 2, 1

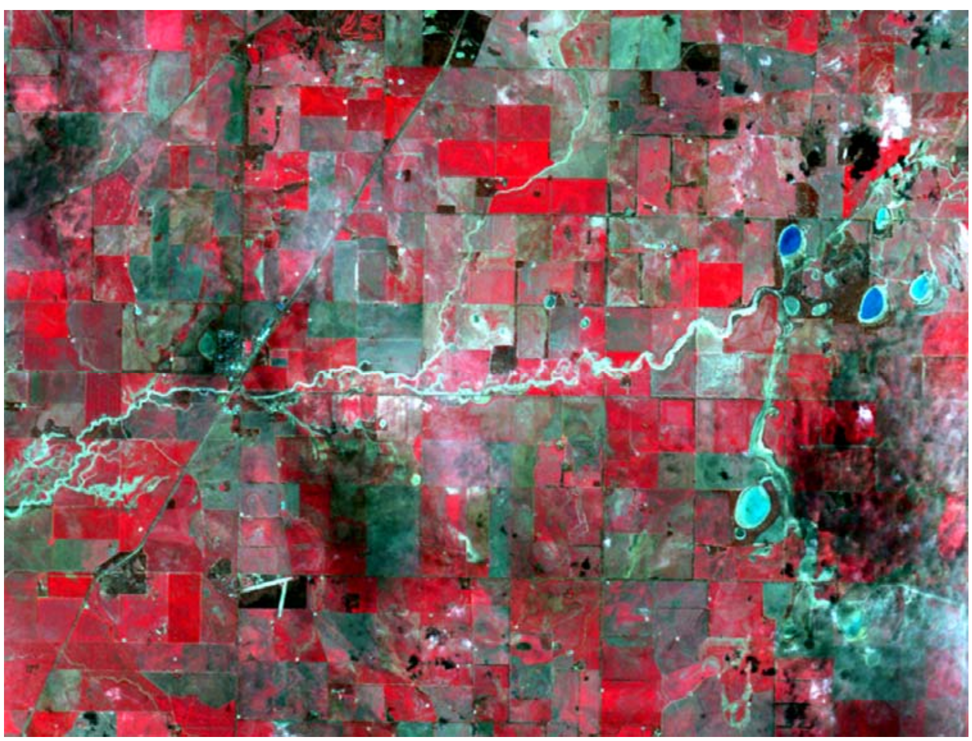


Figure 3-10 Landsat 5 TM image of 3 August 2004 for Narembeen in NIR image NIR, R, G = TM Band 4, 3, 2

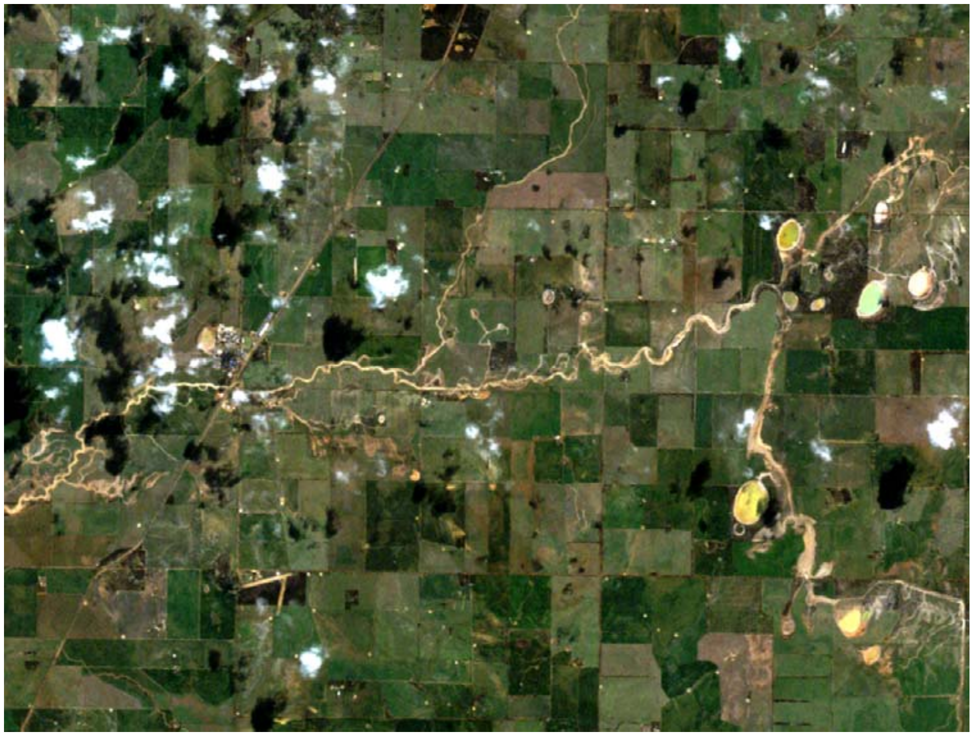


Figure 3-11 Landsat 5 TM image of 21 July 2005 for Narembeen in true colour R, G, B = TM Band 3, 2, 1

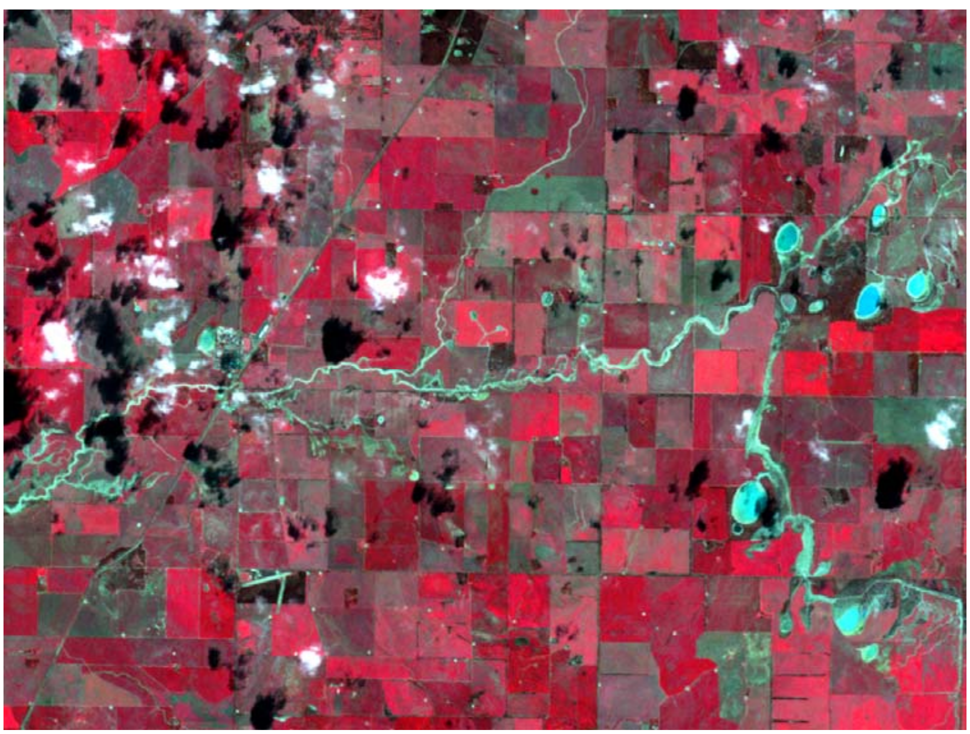


Figure 3-12 Landsat 5 TM image of 21 July 2005 for Narembeen in NIR image NIR, R, G = TM Band 4, 3, 2

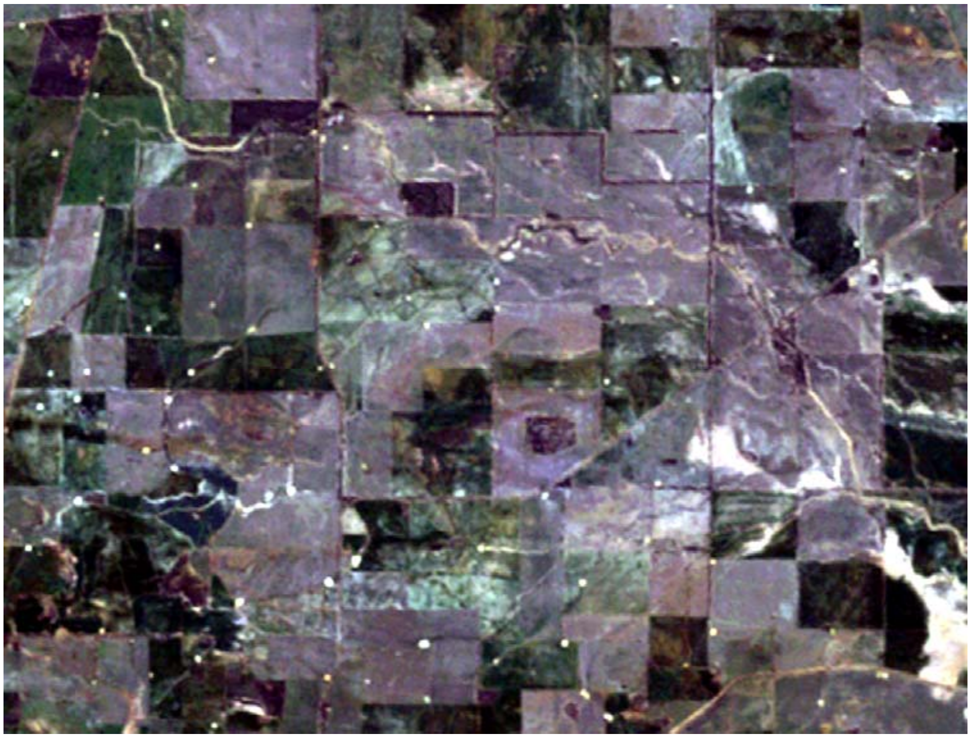


Figure 3-13 Landsat 5 TM image of 14 September 1990 for Dumbleyung in true colour R, G, B = TM Band 3, 2, 1

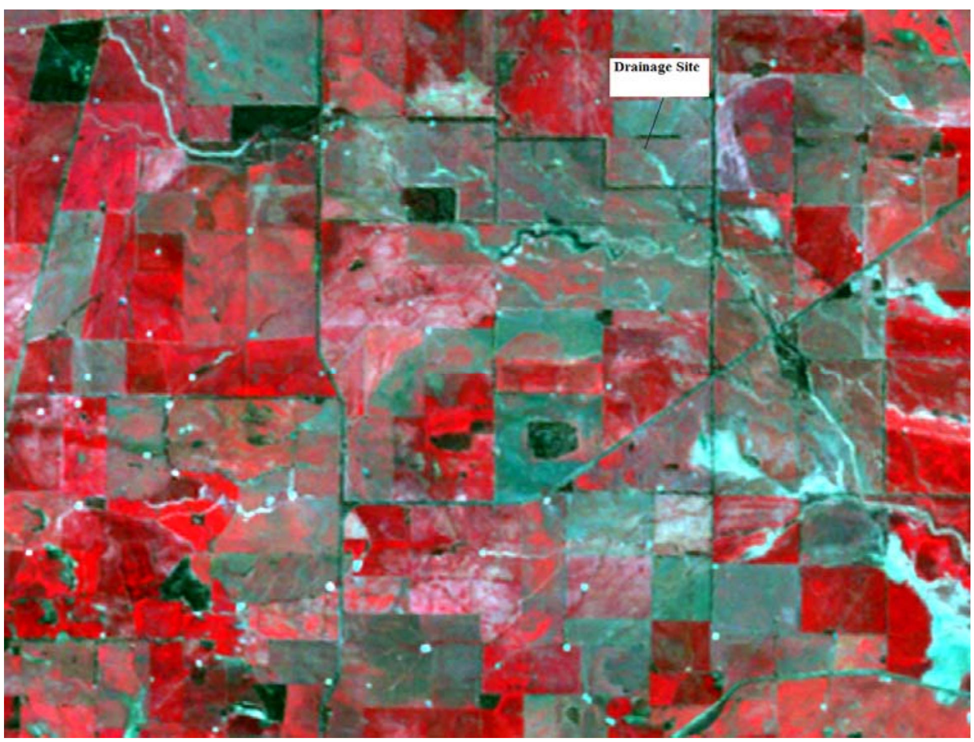


Figure 3-14 Landsat 5 TM image of 14 September 1990 for Dumbleyung in NIR image NIR, R, G = TM Band 4, 3, 2

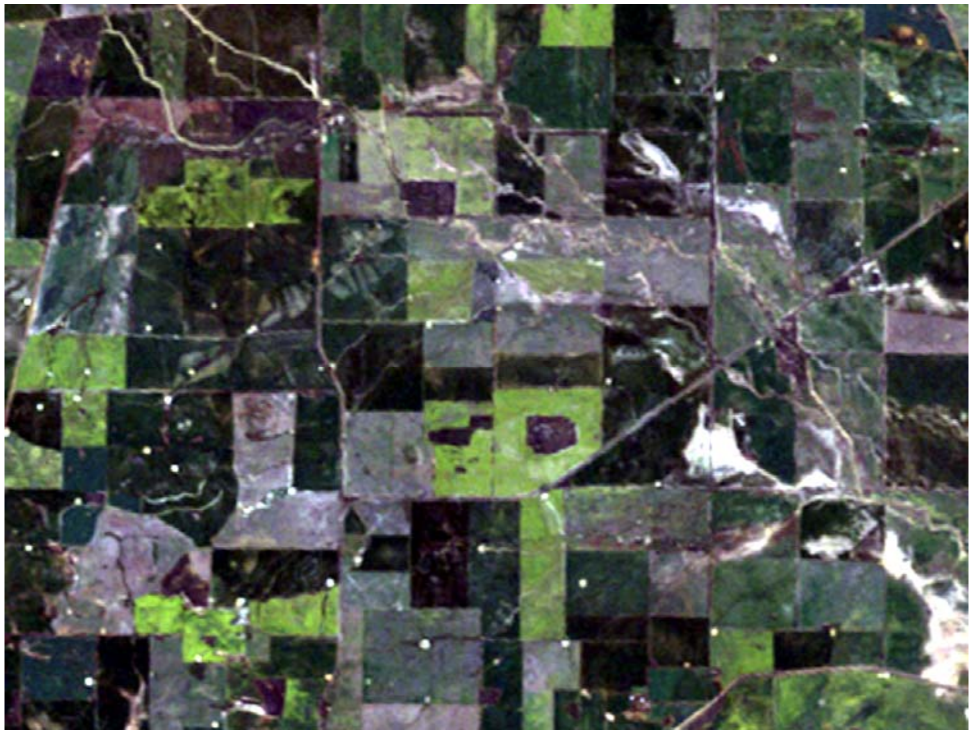


Figure 3-15 Landsat 5 TM image of 14 September 1998 for Dumbleyung in true colour R, G, B = TM Band 3, 2, 1

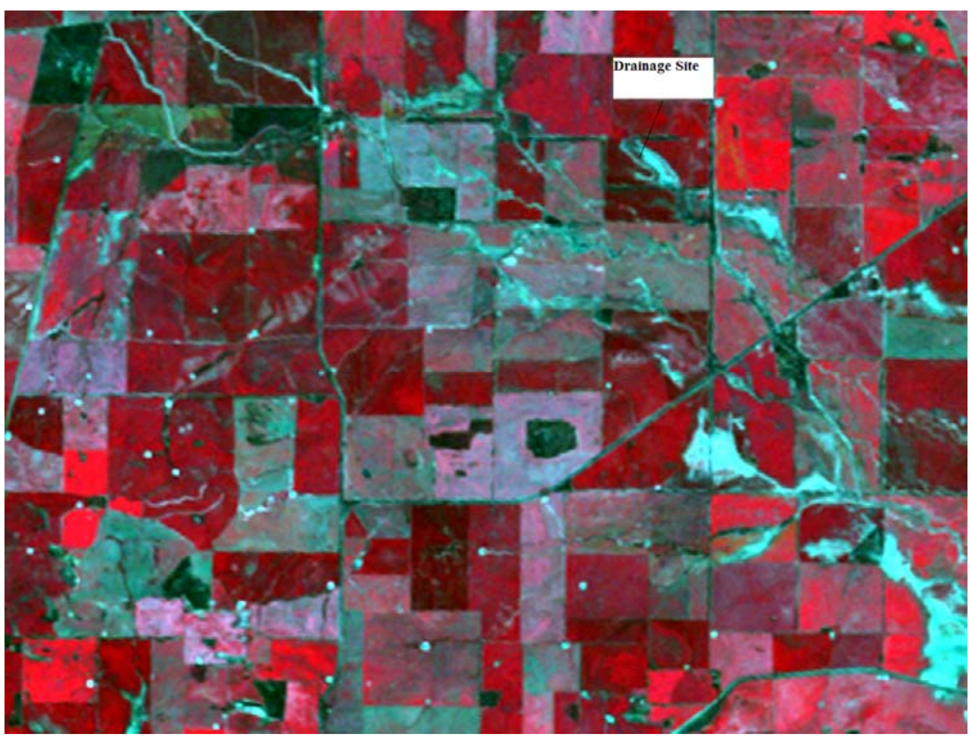


Figure 3-16 Landsat 5 TM image of 14 September 1998 for Dumbleyung in NIR image NIR, R, G = TM Band 4, 3, 2

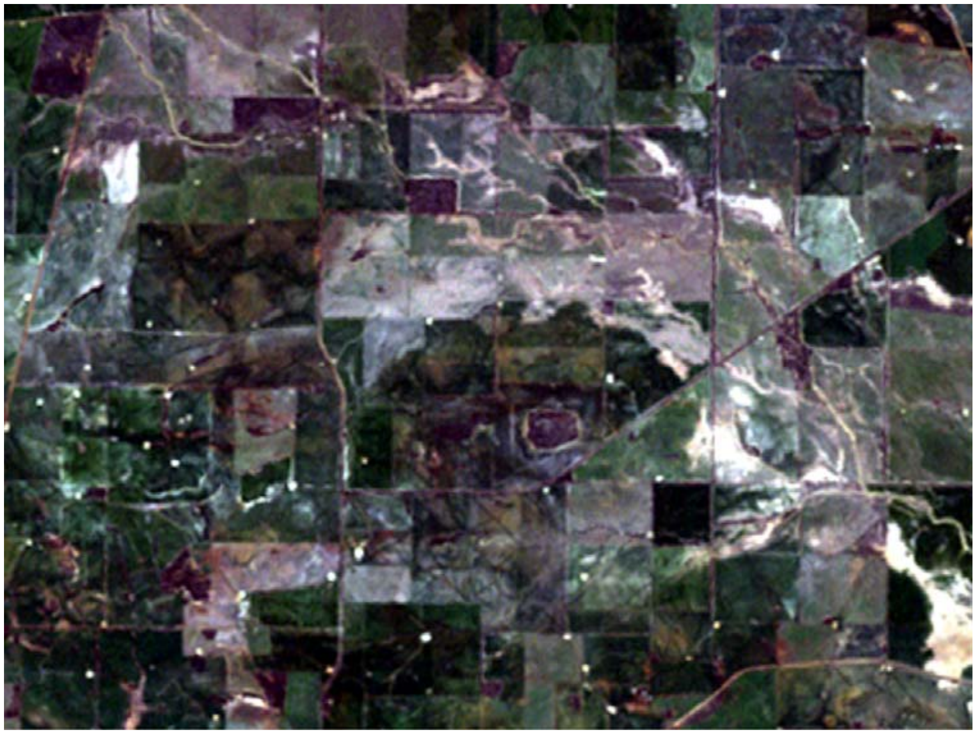


Figure 3-17 Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung in true colour R, G, B = ETM+ Band 3, 2, 1

Figure 3-18 Landsat 5 TM image of 22 August 2002 for Dumbleyung in NIR image NIR, R, G = TM Band 4, 3, 2

Figure 3-19 Landsat 5 TM image of 21 July 2005 for Dumbleyung in true colour
R, G, B = TM Band 3, 2, 1

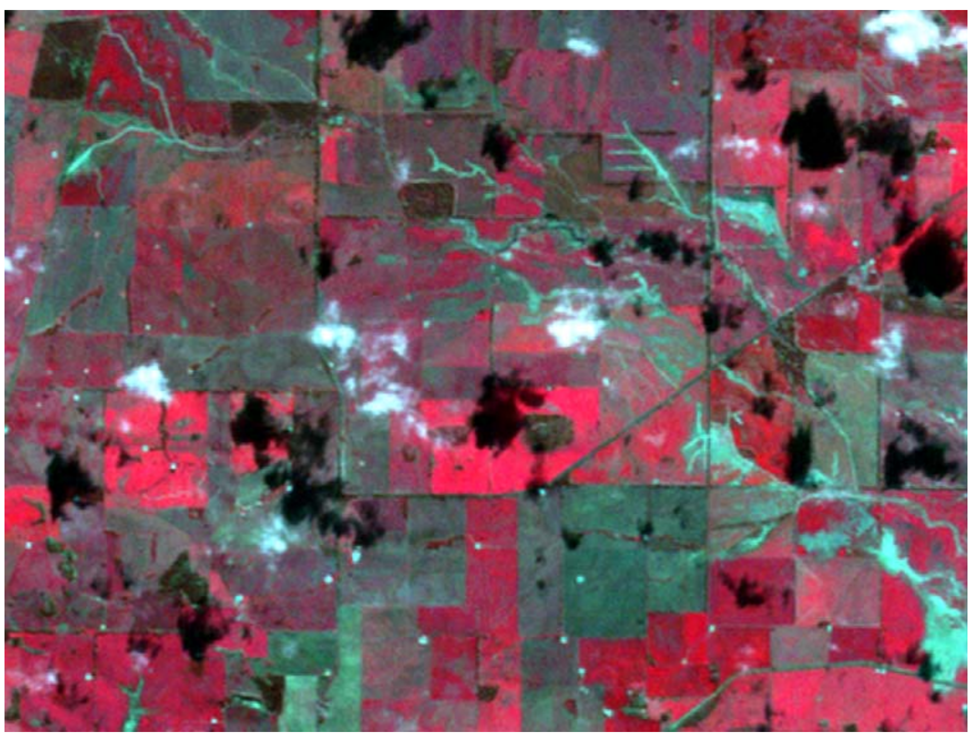


Figure 3-20 Landsat 5 TM image of 21 July 2005 for Dumbleyung in NIR image
NIR, R, G = TM Band 4, 3, 2

3.3.3 The Normalised Difference Vegetation Index (NDVI)

A vegetative index such as a Normalized Difference Vegetation Index (NDVI) is computed from remotely-sensed data to quantify the vegetative cover on the surface of land. The aim of spectral vegetation indices is to enhance the spectral contribution of green vegetation while minimizing contributions from soil background, solar irradiance, sun angle, senescent vegetation and atmosphere by transforming the axes of the multi-dimensional space (Huete, 1989; Kaufman, 1989; Huete and Jackson, 1987).

Spectral signatures were computed for different bands of Landsat Images to delineate areas of salinity and waterlogging. DN of salt-affected soils was relatively higher than other categories in band-1 and band-3. An indication of whether scanty vegetation in an area was due to high watertable depth or salinity was investigated using Normalized Differential Vegetation Index (NDVI).

The NDVI is calculated from a TM-scene by taking the ratio of the difference of the near infrared and red reflection and the sum between these two bands using formula

NDVI = (NIR Band - Red Band) / (NIR Band + Red Band)

The NDVI values ranges between 1 and –1. It is near 0.8 for completely vegetated areas to 0.05 for completely bare soil, and near –0.5 for bodies of water.

In order to maximize the range of the NDVI values it can be scaled to display on a gray tone. The scaling converts a number between -1.0 and 1.0 into a pixel value from 0 to 200 by using the Equation 3-1.

$$\text{Scaled NDVI} = 100(\text{NDVI} + 1) \qquad 3\text{-}1$$

The scaled NDVI will have the range of 0 to 200, where computed -1.0 equals 0, computed 0 equals 100, and computed 1.0 equals 200. The pixel with an NDVI value of 0.40 would be scaled into a gray scale value of 140. As a result, NDVI values less than 100 will represent clouds, snow, water, and other non-vegetative surfaces, and values equal to or greater than 100 represent vegetative surfaces (http://chesapeake.towson.edu/data/all_ndvi.asp).

Landsat images were opened in ER Mapper using 3, 4 and 1 layers (R, NIR and B bands). A pseudocolour mode and greyscale colour table was selected from the Surface menu. The scaled NDVI formula was added in the FORMULA EDITOR and was saved in a file for using it for different images. After applying the scaled NDVI formula the image was refreshed from Image Refresh button and then Image Refresh with 99% clip on limits button. Landsat 5 TM image of 10 August 1989 for Narembeen after applying scaled NDVI is given in Figure 3-21. Lighter shades of grey indicate an abundance of healthy vegetation. The image appears dark if there is little or no vegetation and image appears black in areas of water.

3.3.4 NDVI for Narembeen

The scaled NDVI was applied to Landsat images from 1989 to 2005 for Narembeen and the resulting greyscaled images are presented in Figures 3-21 to 3-26. Some parts of the drain at Narembeen were installed in 1998 and 1999. Ali *et al*., (2004) reported that at the Narembeen site it took one to two years for the water-table to recede after the drain was installed. The pre- and post-drainage mean NDVI of Landsat images for Narembeen with standard deviation from 1989 to 2005 are given in Table 3-2. Both Landsat images of 3 August 2004 and 21 July 2005 have cloud cover and mean NDVI values cannot be compared with mean NDVI of previous years. The only post-drainage Landsat image of 22 August 2002 is available and it was low rainfall year that caused crops to fail. The highest mean NDVI of 161 (Std. Dev. of 54) for Narembeen was observed in 1996. The lowest mean NDVI of 118 (Std. Dev. of 59) for Narembeen was observed in 2002.

Table 3-2 Mean NDVI of Narembeen from 1989 to 2005

Landsat Sensor	Date of Capture (Satellite Overpass)	Mean NDVI of Narembeen	Standard Deviation
TM	10-Aug-89	142	0
TM	8-Aug-94	129	57
TM	29-Aug-96	161	54
TM	22-Aug-02	118	59
TM	3-Aug-04	121	56
TM	21-Jul-05	139	56

Figure 3-21 NDVI applied to Landsat 5 TM image of 10 August 1989 for Narembeen

Figure 3-22 NDVI applied to Landsat 5 TM image of 8 August1994 for Narembeen

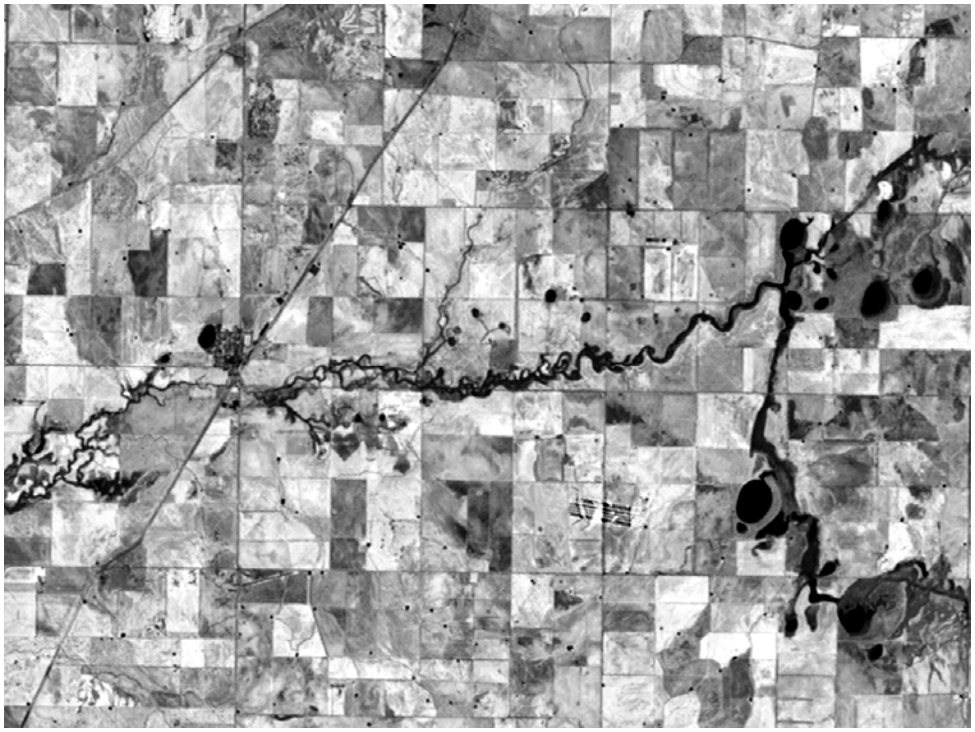


Figure 3-23 NDVI applied to Landsat 5 TM image of 29 August 1996 for Narembeen

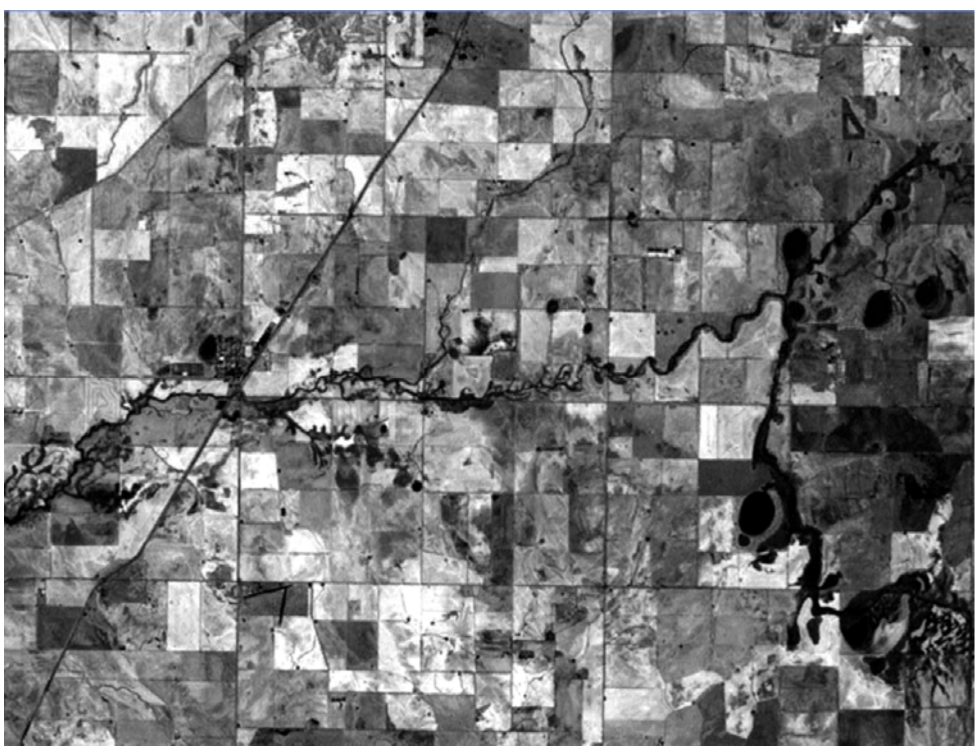


Figure 3-24 NDVI applied to Landsat 5 TM image of 22 August 2002 for Narembeen

Figure 3-25 NDVI applied to Landsat 5 TM image of 3 August 2004 for Narembeen

Figure 3-26 NDVI applied to Landsat 5 TM image of 21 July 2005 for Narembeen

3.3.5 NDVI for Dumbleyung

The scaled NDVI was applied to Landsat images from 1990 to 2005 for Dumbleyung and the resulting greyscaled images are presented in Figures 3-27 to 3-30. The deep open drains in Dumbleyung were installed in December, 2003. The pre- and post-drainage mean NDVI of Landsat images for Dumbleyung with standard deviation from 1990 to 2005 are given in Table 3-3. The Landsat image of 3 August 2004 had a complete cloud cover and it was not considered for the analysis. The Landsat image of 21 July 2005 have a partial cloud cover and mean NDVI values cannot be compared with mean NDVI of previous years. The only post-drainage Landsat image of 22 August 2002 is available and it was a low rainfall year and crop production was low in 2002. The highest mean NDVI of 149 (Std. Dev. of 57) for Dumbleyung was observed in 1998. The lowest mean NDVI of 126 (Std. Dev. of 58) for Dumbleyung was observed in 1996.

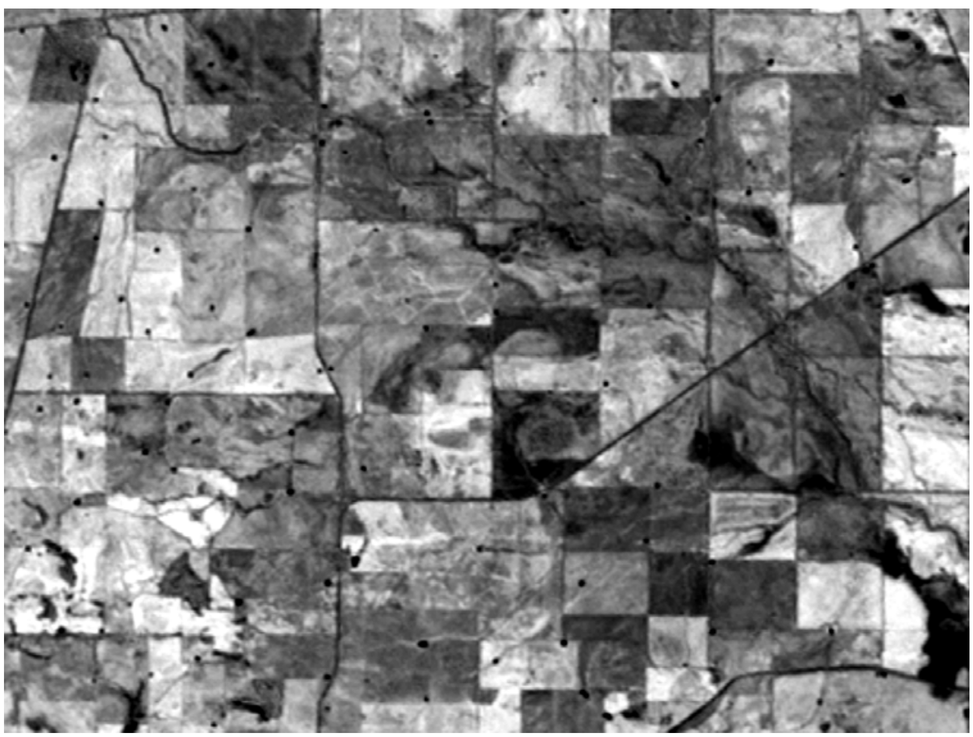


Figure 3-27 NDVI applied to Landsat 5 TM image of 14 September 1990 for Dumbleyung

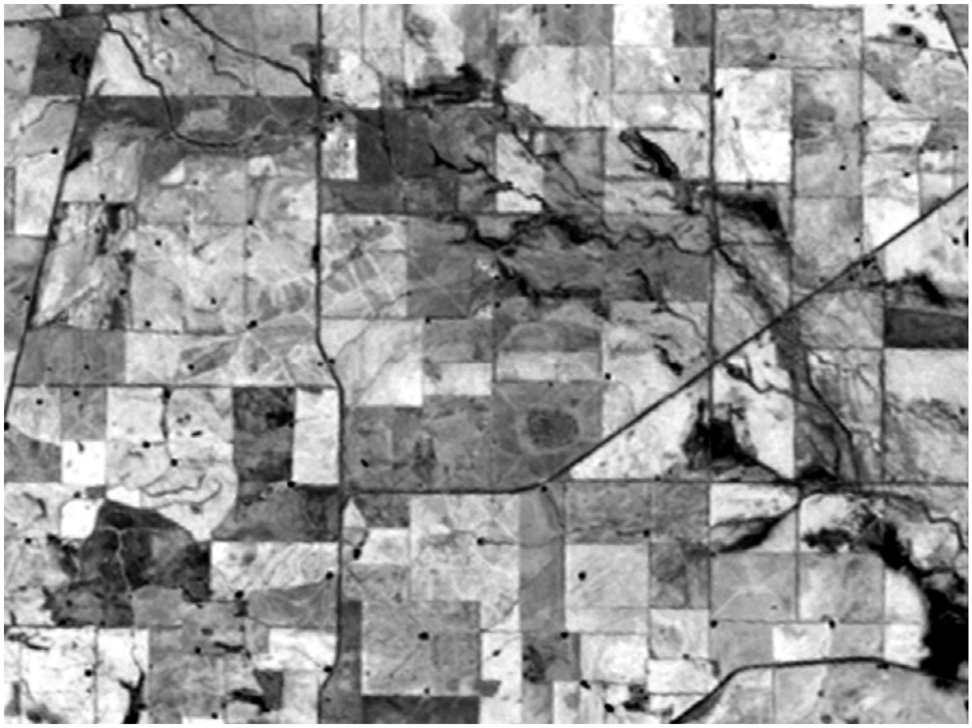


Figure 3-28 NDVI applied to Landsat 5 TM image of 14 September 1998 for Dumbleyung

Figure 3-29 NDVI applied to Landsat 5 TM image of 22 August 2002 for Dumbleyung

Figure 3-30 NDVI applied to Landsat 5 TM image of 21 July 2005 for Dumbleyung

Table 3-3 Mean NDVI of Narembeen from 1990 to 2005

Landsat Sensor	Date of Capture (Satellite Overpass)	Mean NDVI of Dumbleyung	Standard Deviation
TM	14-Sep-90	126	58
TM	29-Aug-98	149	57
TM	22-Aug-02	138	62
TM	21-Jul-05	138	63

The scaled NDVI value of three transects digitised using Transverse command of ER Mapper along the deep drains on Landsat 5 TM image of 21 July 2005 of Dumbleyung. In the first transect scaled NDVI values on the left of drain dropped from 150 to 100 at distance 100 m from the collector drain. On the right side of drain scaled NDVI values were 150 or more but 50 m from drain below 100. If scaled NDVI values are below 100 there was no vegetation. In the second transect scaled NDVI values on the left of drain dropped from more than 150 to 135 and then at distance 200 m from the collector drain values dropped below 100. On the right side of drain scaled NDVI values were 125 only at some locations. In the third transect scaled NDVI values on the left of drain were between 125 and 150 and because of cloud the value dropped below 100 and then rose back to more than 150.

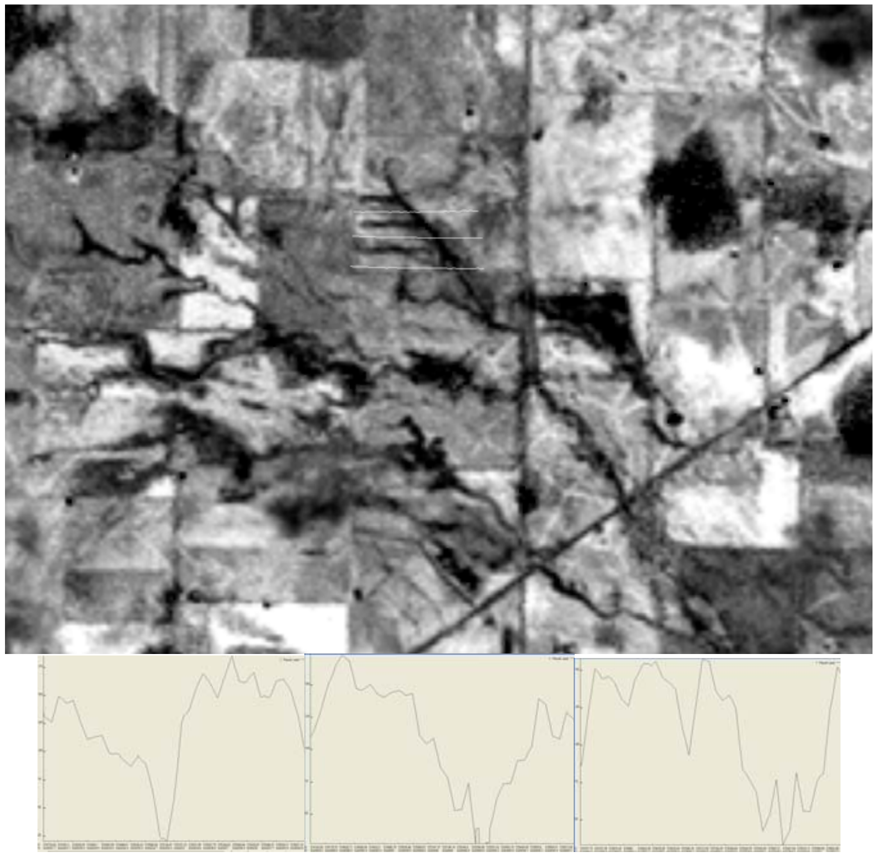


Figure 3-31 The scaled NDVI value of three transects on Landsat 5 TM image of 21 July 2005 of Dumbleyung

Two salinity indices namely, SI (Salinity Index) and NDSI (Normalized Differential Salinity Index) were applied to Narembeen and Dumbleyung images in the following sections.

3.3.6 Salinity Index

A salinity index (SI) shown in Equation 3-2 was proposed by Tripathi *et al*., (1997) to classify the salt-affected lands.

$$SI = \sqrt{Band1 * Band2} \qquad \text{3-2}$$

Landsat images were opened in ER Mapper using 3, 2 and 1 layers (R, G and B bands). A RGB colour mode was selected from the Surface menu. The SI formula was added in the FORMULA EDITOR and was saved in a file for using it for different images. After applying the SI formula the image was refreshed from Image Refresh button and then Image Refresh with 99% clip on limits button. Landsat 5 TM image of 10 August 1989 for Narembeen after applying scaled SI is given in Figure 3-31. Shades of purple indicate the saline, waterlogged and degraded areas. The SI was applied to Landsat images from 1989 to 2005 for Narembeen and the resulting RGB images are presented in Figures 3-31 to 3-35. Visual interpretation of the images for Narembeen indicates that saline, waterlogged and degraded areas have decreased from 1989 to 2005.

The SI was applied to Landsat images from 1990 to 2005 for Dumbleyung and the resulting RGB images are presented in Figures 3-36 to 3-40. Visual interpretation of the images for Dumbleyung indicates that saline, waterlogged and degraded areas have increased from 1990 to 1998, decreased in 2002 and slight increase in 2005.

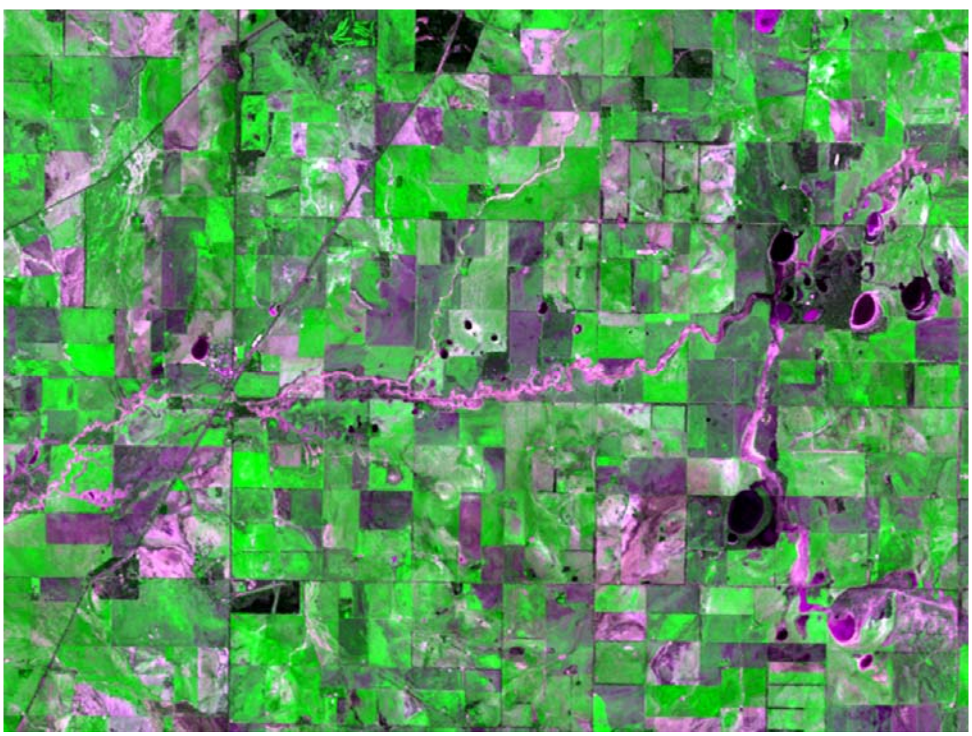


Figure 3-32 SI applied to Landsat 5 TM image of 10 August 1989 for Narembeen

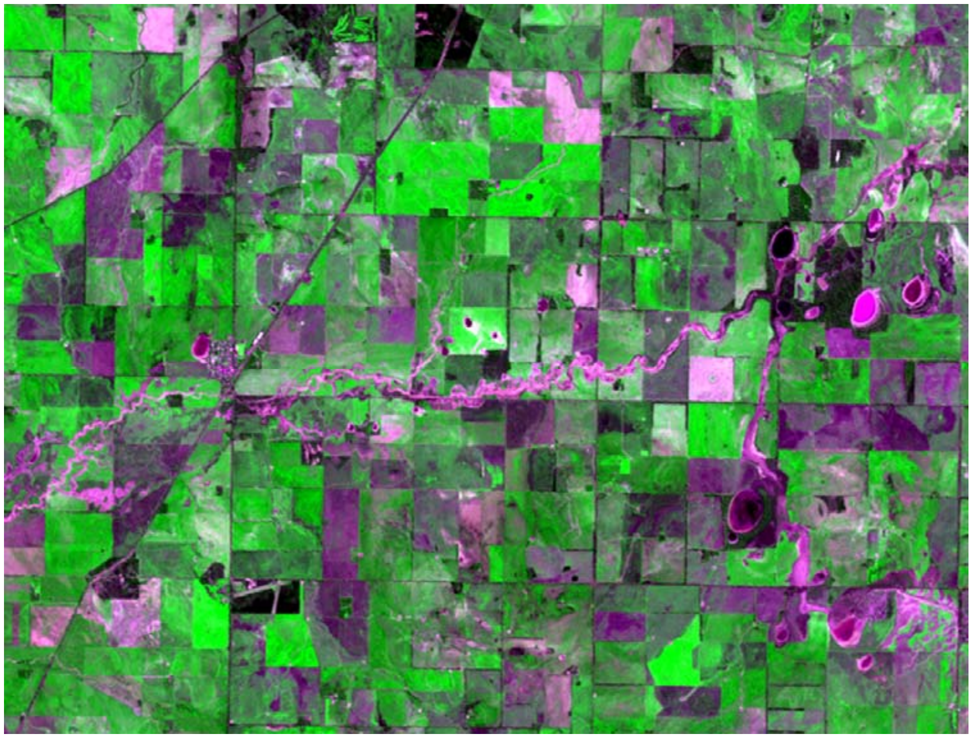


Figure 3-33 SI applied to Landsat 5 TM image of 8 August 1994 for Narembeen

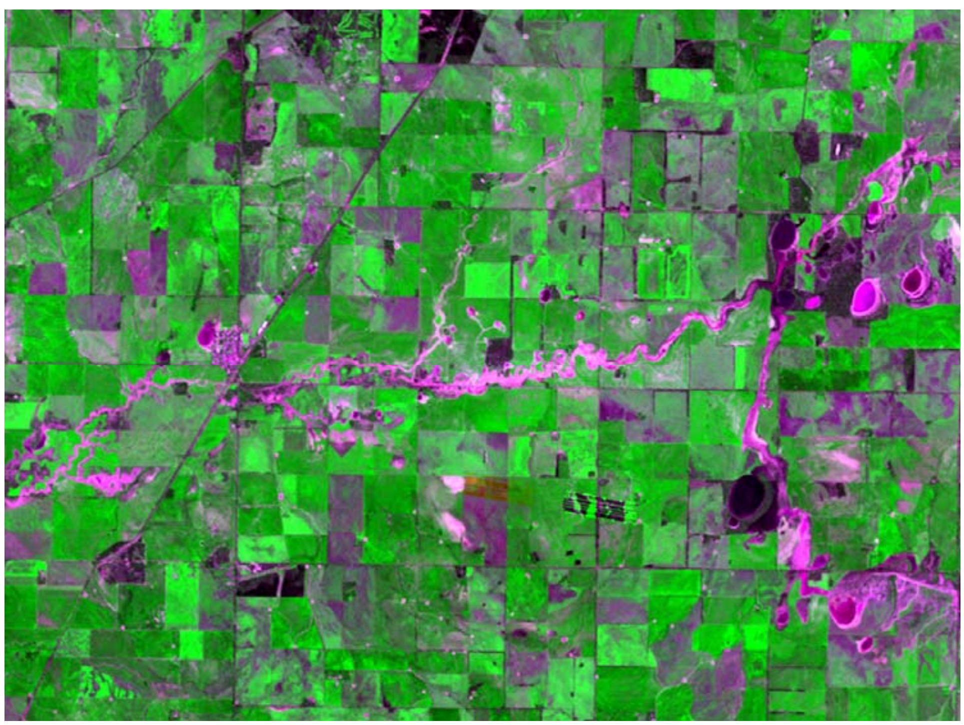


Figure 3-34 SI applied to Landsat 5 TM image of 29 August 1996 for Narembeen

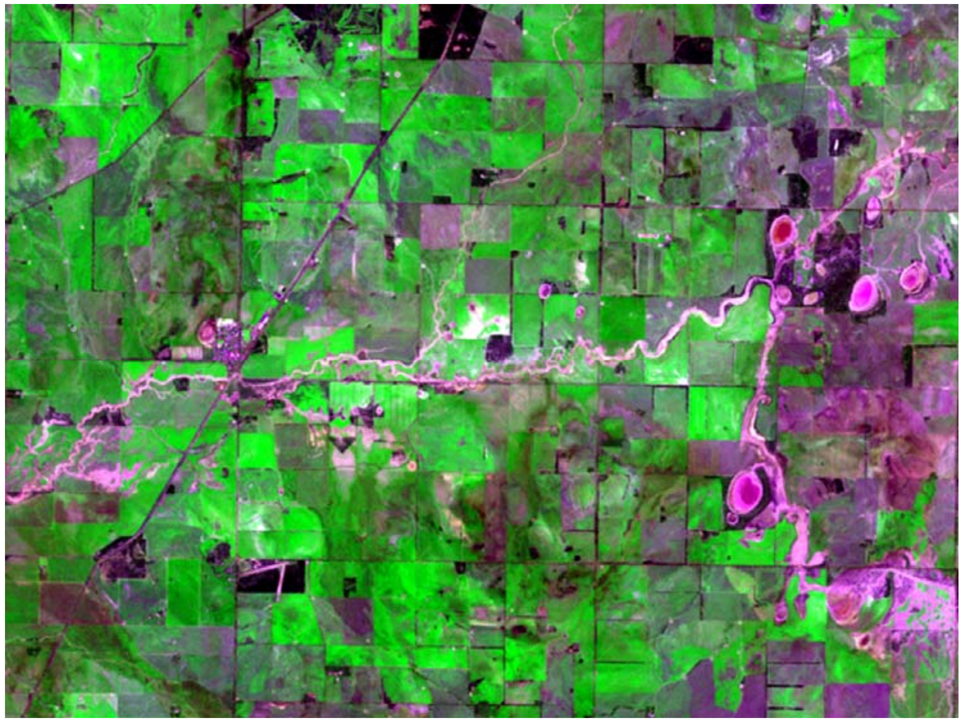


Figure 3-35 SI applied to Landsat 5 TM image of 22 August 2002 for Narembeen

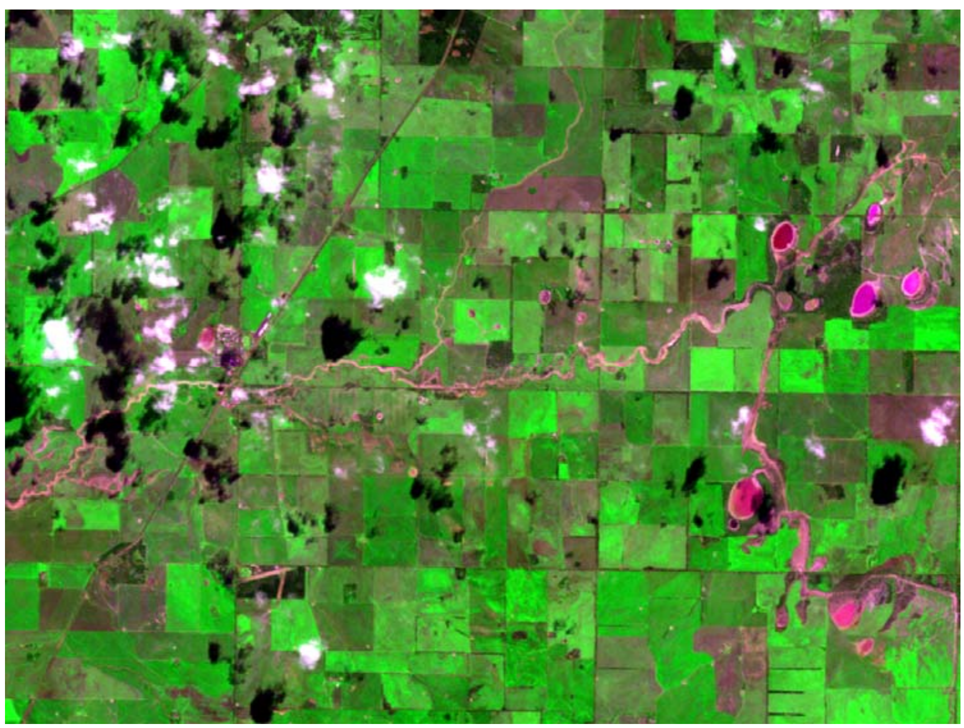


Figure 3-36 SI applied to Landsat 5 TM image of 21 July 2005 for Narembeen

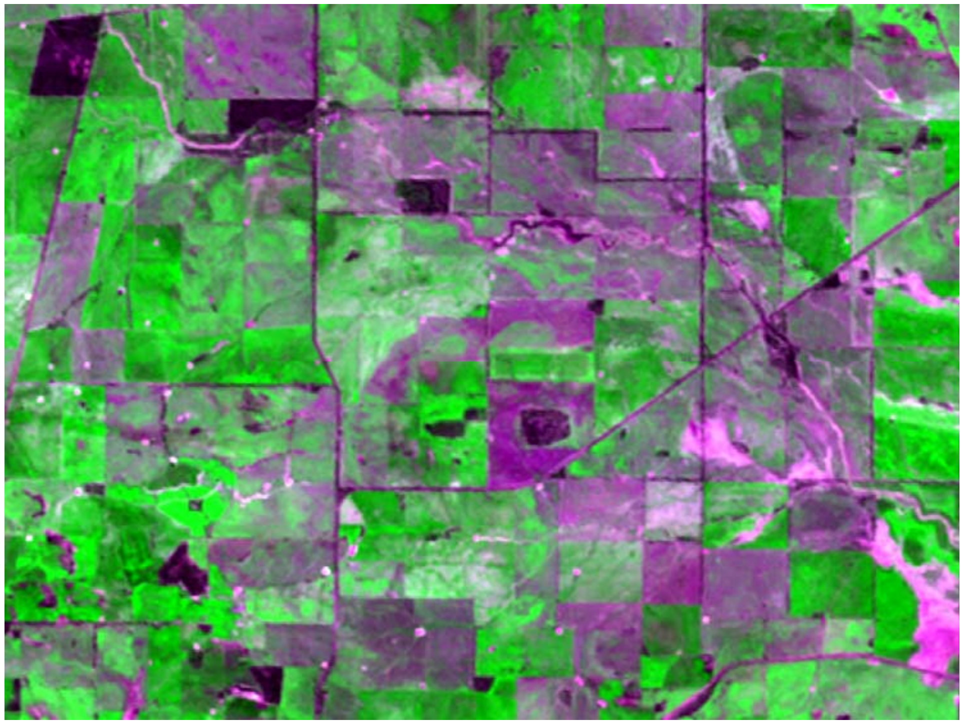


Figure 3-37 SI applied to Landsat 5 TM image of 14 September 1990 for Dumbleyung

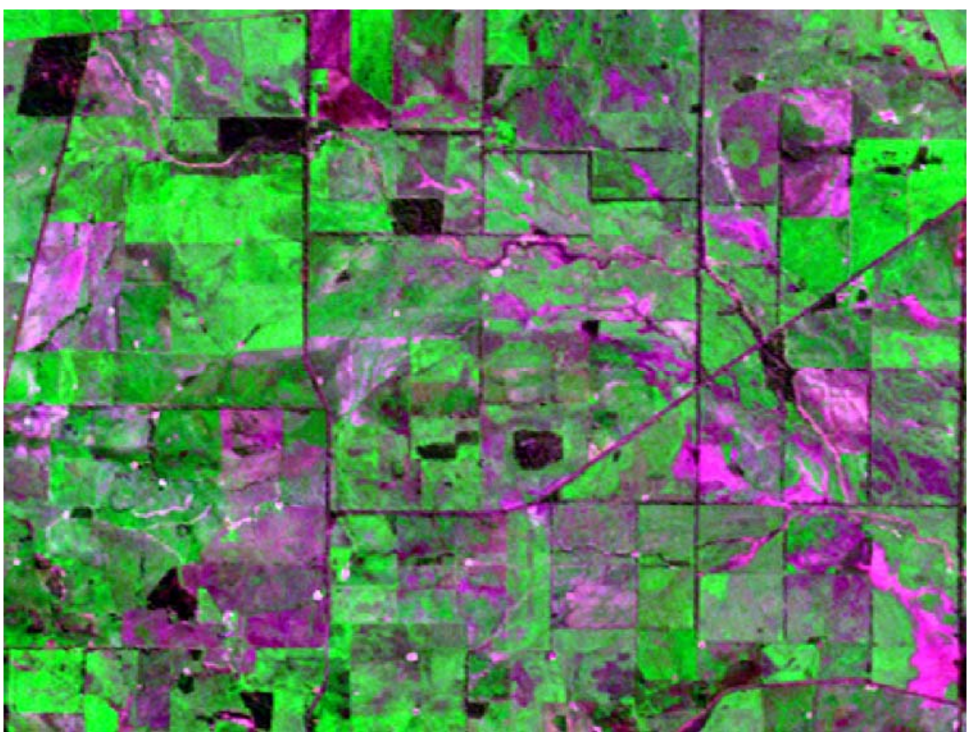


Figure 3-38 SI applied to Landsat 5 TM image of 8 August1994 for Dumbleyung

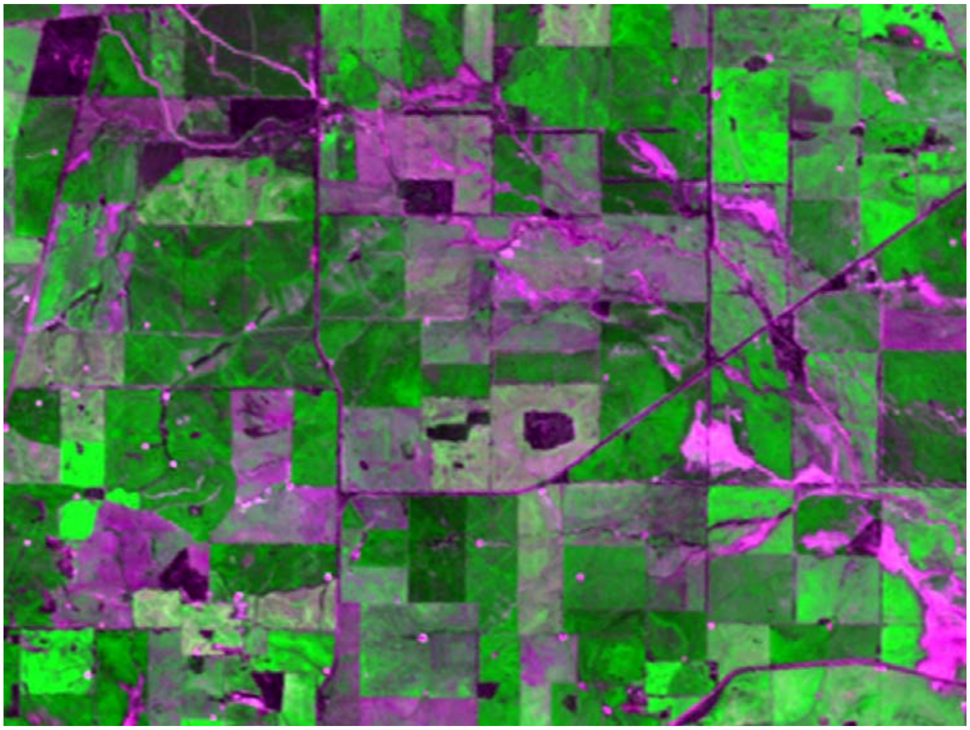


Figure 3-39 SI applied to Landsat 5 TM image of 14 September 1998 for Dumbleyung

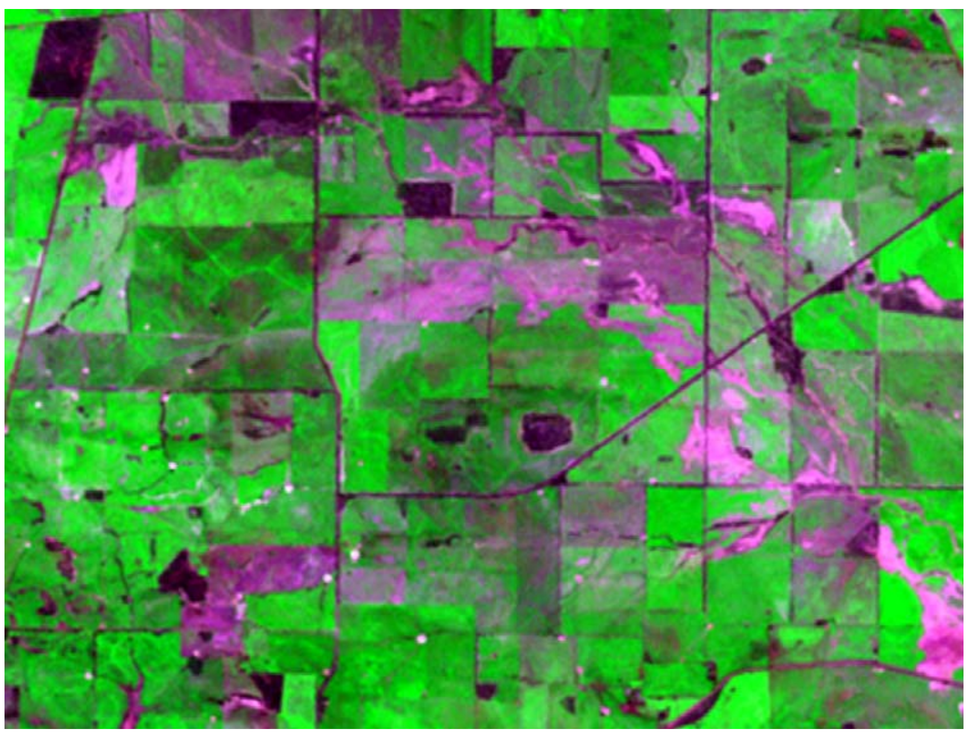


Figure 3-40 SI applied to Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung

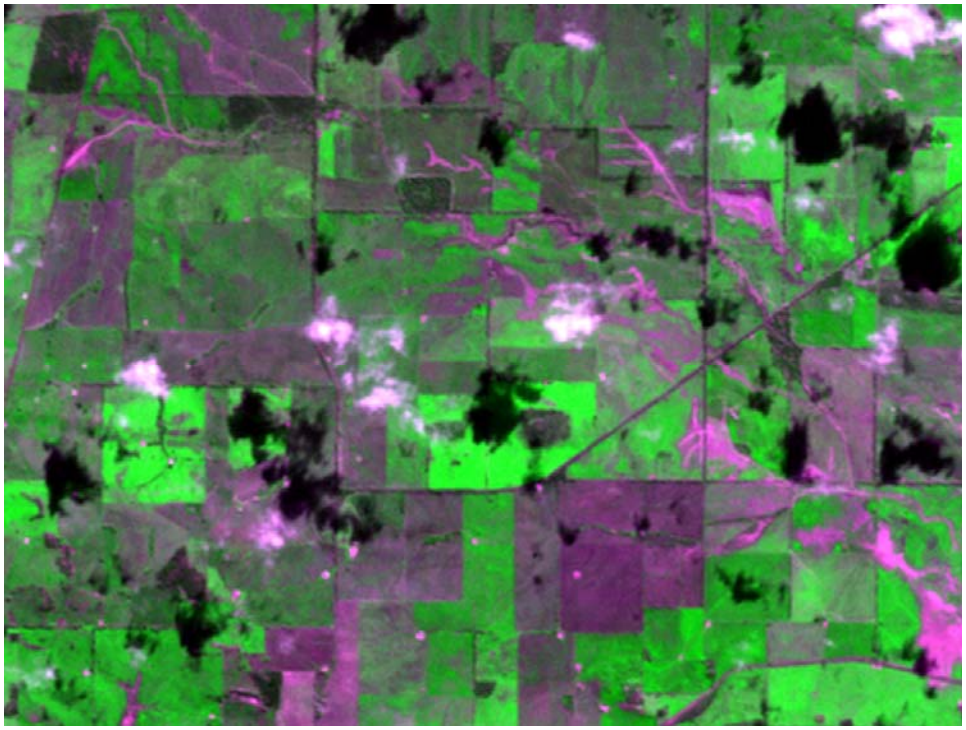


Figure 3-41 SI applied to Landsat 5 TM image of 21 July 2005 for Dumbleyung

3.3.7 Normalized Differential Salinity Index

A Normalized Differential Salinity Index (NDSI) shown in Equation 3-3 was proposed by Tripathi *et al*., (1997) to classify the salt-affected lands.
NDSI is just the reverse of NDVI and is given by the Equation 3-3.

NSDI = (Band 3 - Band 4) / (Band 3 + Band 4) 3-3

Landsat images were opened in ER Mapper using 3, 4 and 1 layers (R, NIR and B bands). A RGB colour mode was selected from the Surface menu. The NDSI formula was added in the FORMULA EDITOR and was saved in a file for using it for different images. After applying the NDSI formula the image was refreshed from Image Refresh button and then Image Refresh with 99% clip on limits button. Landsat 5 TM image of 10 August 1989 for Narembeen after applying scaled NDSI is given in Figure 3-42. Shades of red indicate the saline, waterlogged and degraded areas. All metal roads, farm roads with trees, lakes, drains and farm remnant vegetation reserves in the area are in shades of red. The cropped area is in shades of green. The NDSI was applied to Landsat images from 1989 to 2005 for Narembeen and the resulting RGB images are presented from Figure 3-41 to Figure 3-45. Visual interpretation of the images for Narembeen indicates that saline, waterlogged and degraded areas have decreased from 1989 to 2005.

The NDSI was applied to Landsat images from 1990 to 2005 for Dumbleyung and the resulting RGB images are presented in Figures 3-46 to 3-50. Visual interpretation of the images for Dumbleyung indicates that saline, waterlogged and degraded areas have increased from 1990 to 1998, decreased in 2002 and slightly increased in 2005.

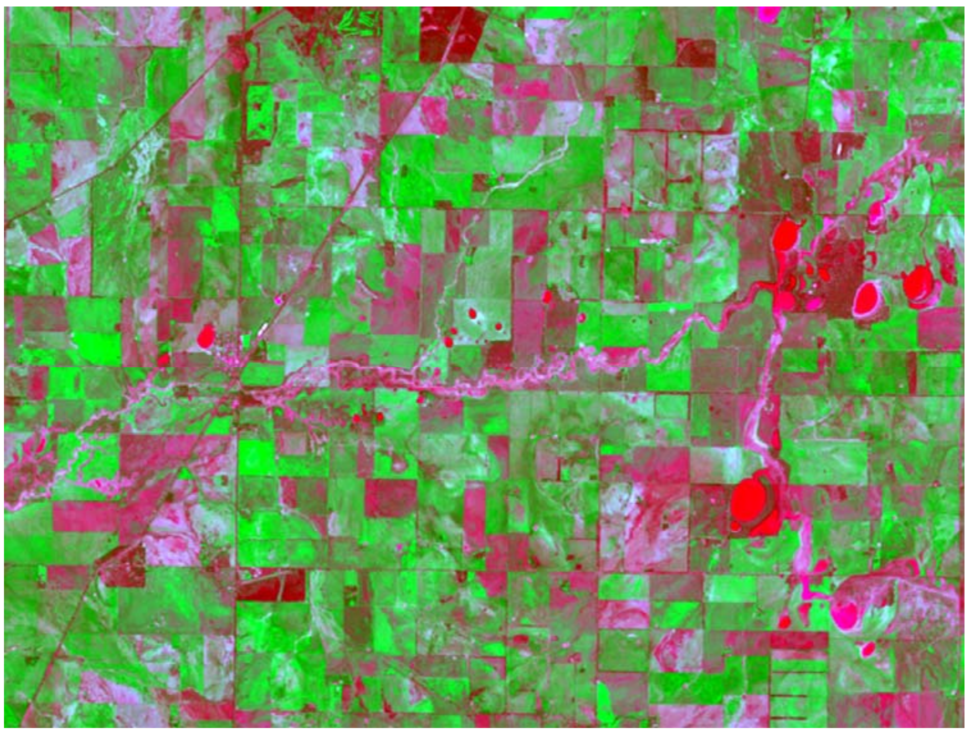


Figure 3-42 NDSI applied to Landsat 5 TM image of 10 August 1989 for Narembeen

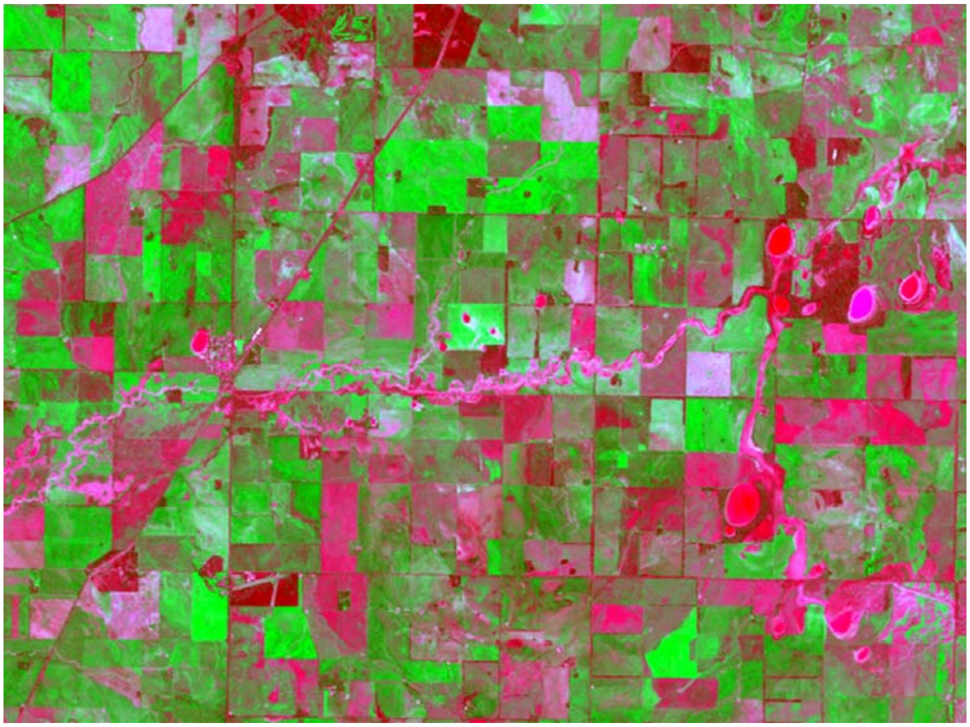


Figure 3-43 NDSI applied to Landsat 5 TM image of 8 August1994 for Narembeen

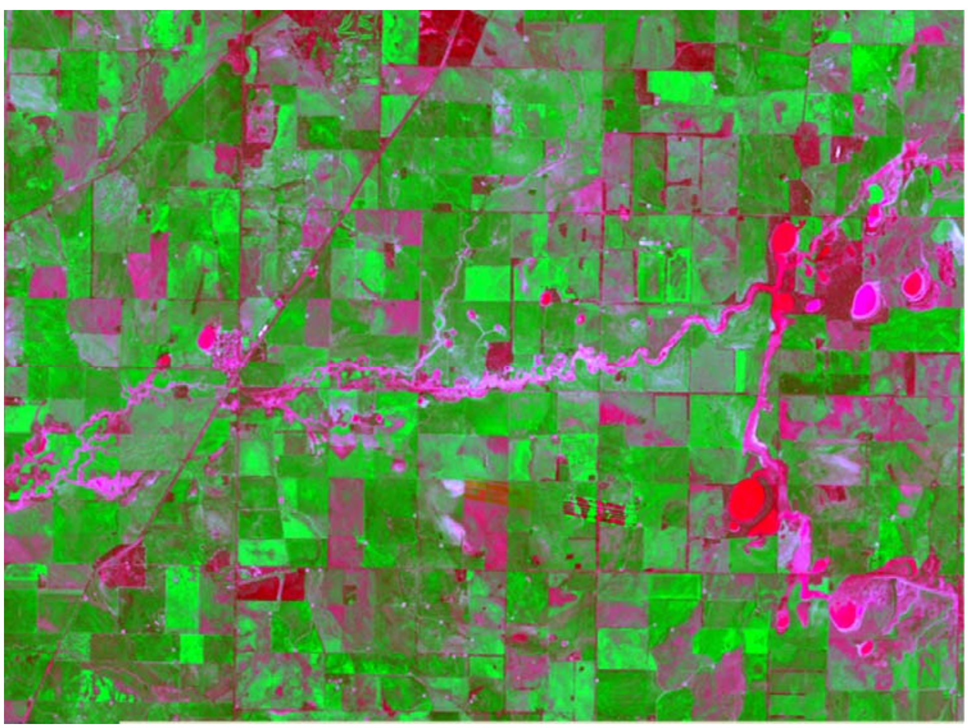


Figure 3-44 NDSI applied to Landsat 5 TM image of 29 August 1996 for Narembeen

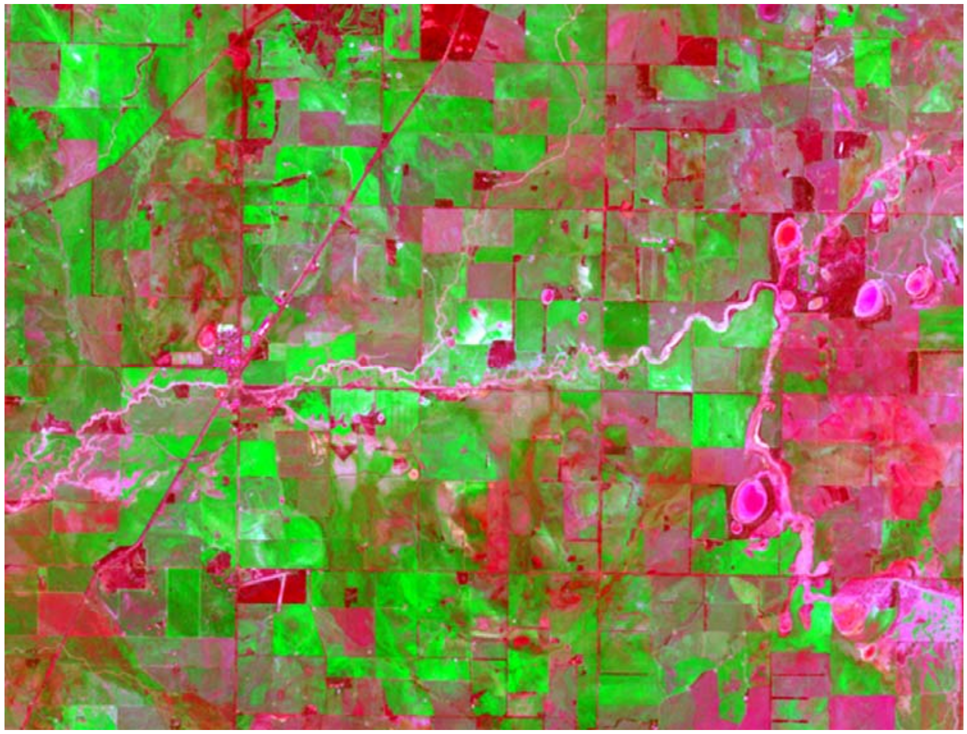


Figure 3-45 NDSI applied to Landsat 7 ETM+ image of 22 August 2002 for Narembeen

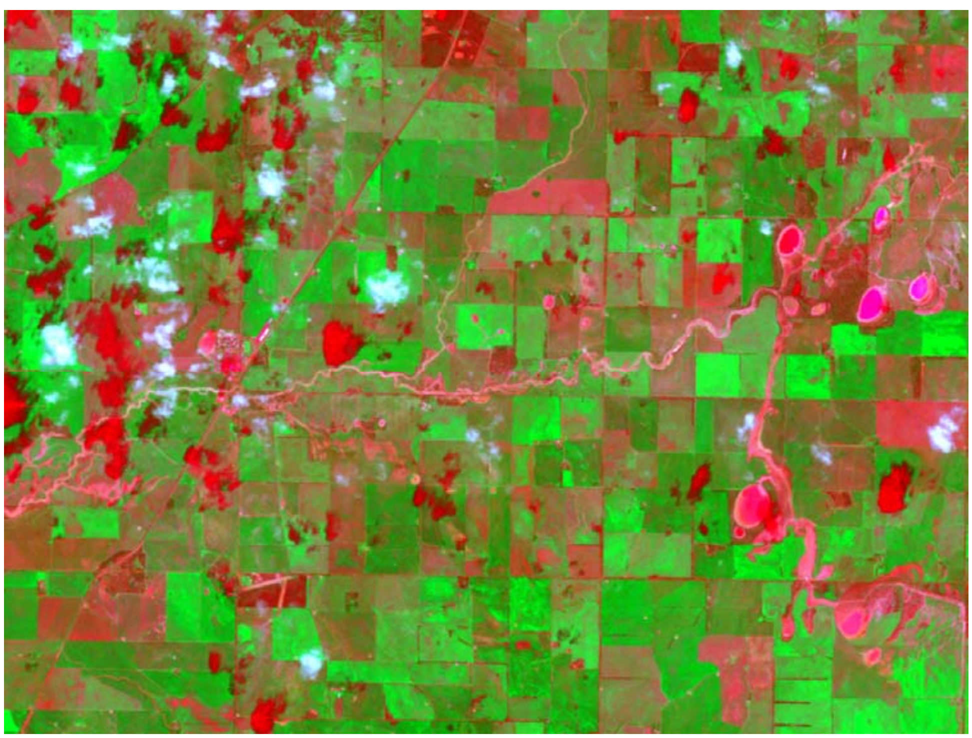


Figure 3-46 NDSI applied to Landsat 5 TM image of 21 July 2005 for Narembeen

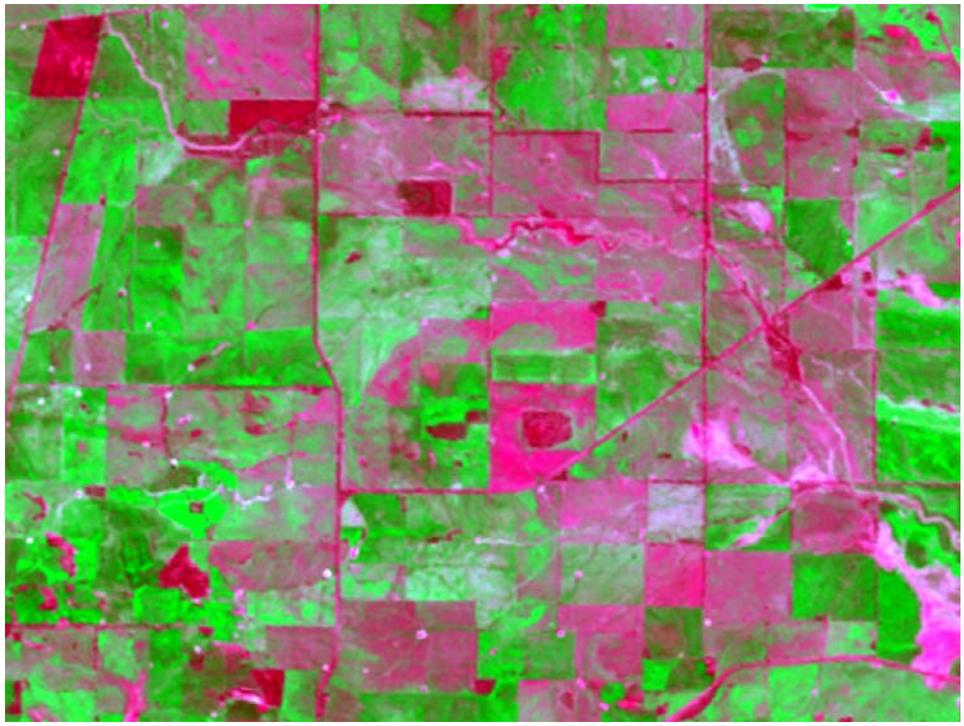


Figure 3-47 NDSI applied to Landsat 5 TM image of 14 September 1990 for Dumbleyung

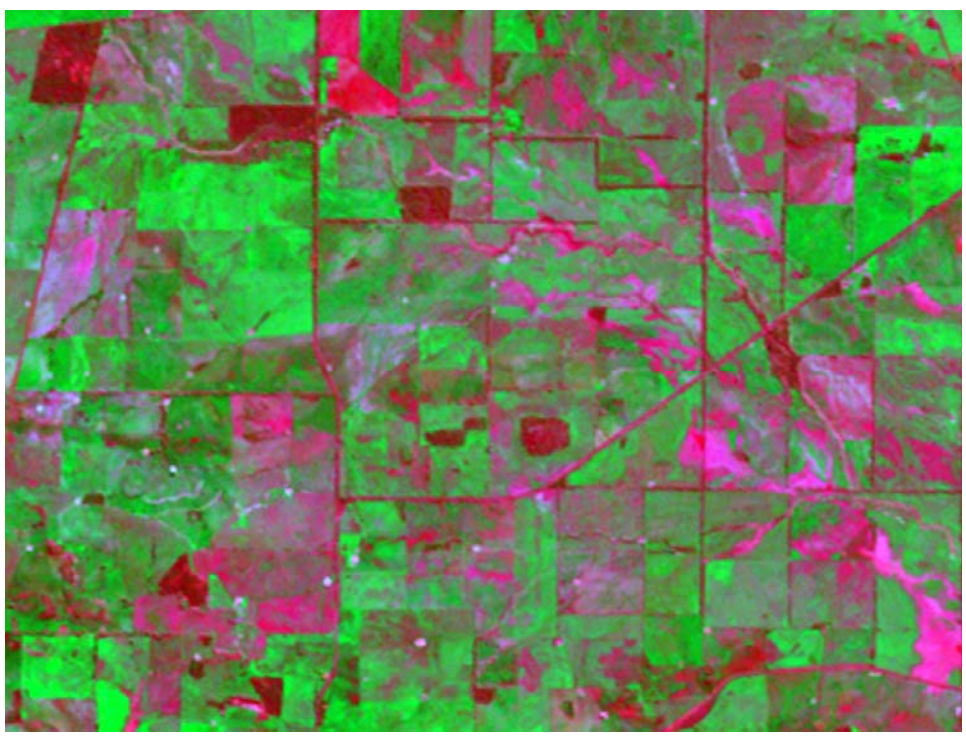


Figure 3-48 NDSI applied to Landsat 5 TM image of 8 August1994 for Dumbleyung

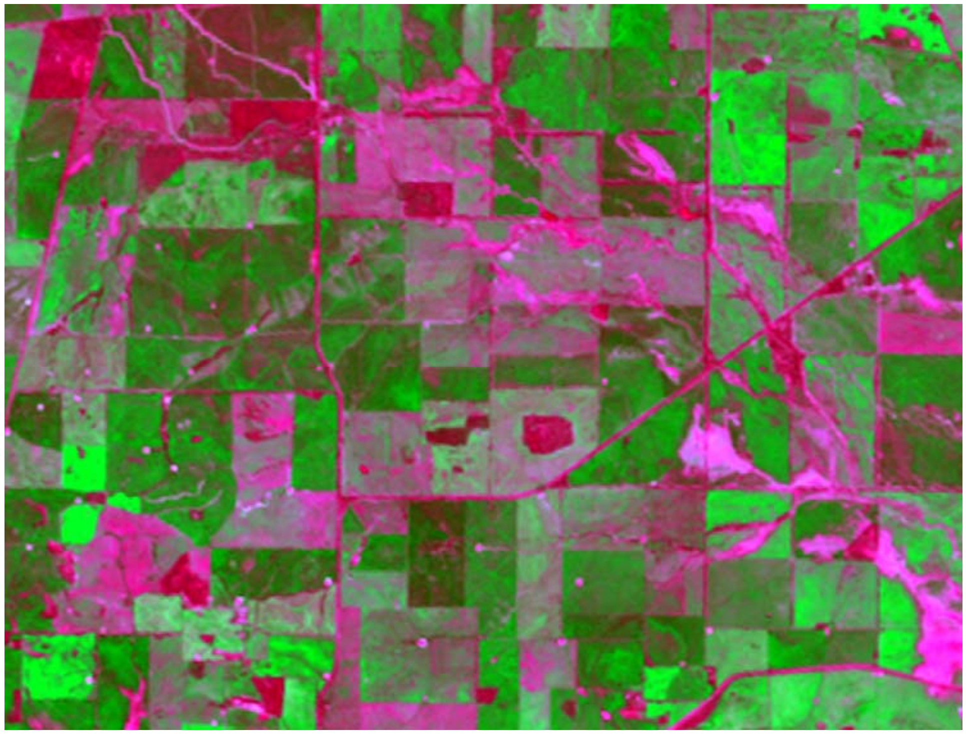


Figure 3-49 NDSI applied to Landsat 5 TM image of 14 September 1998 for Dumbleyung

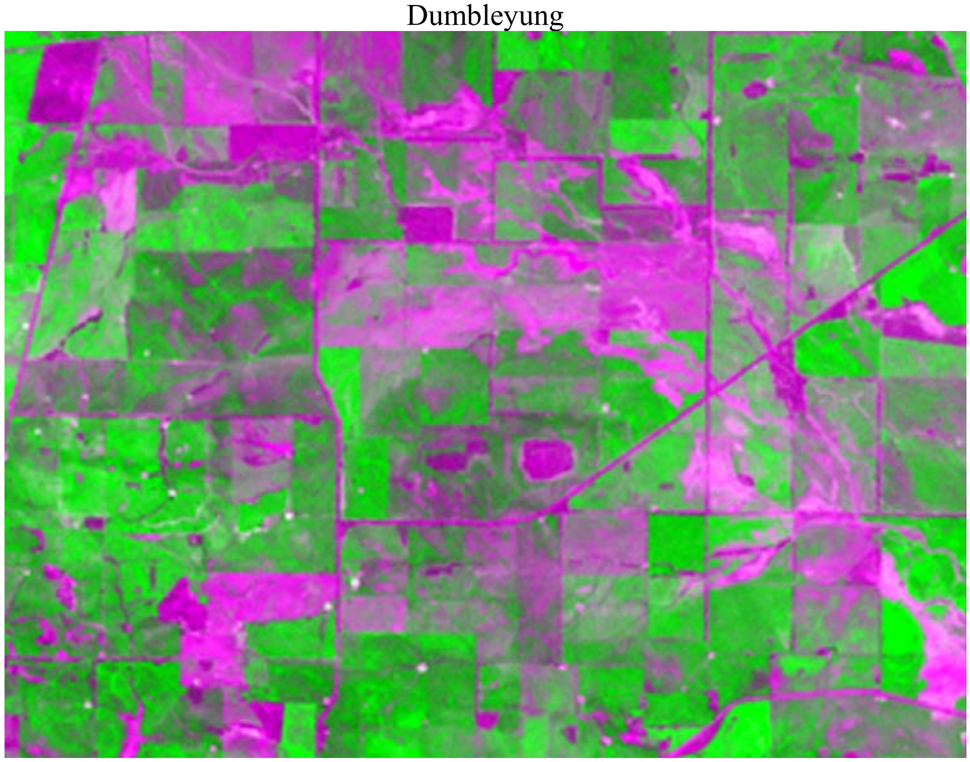


Figure 3-50 NDSI applied to Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung

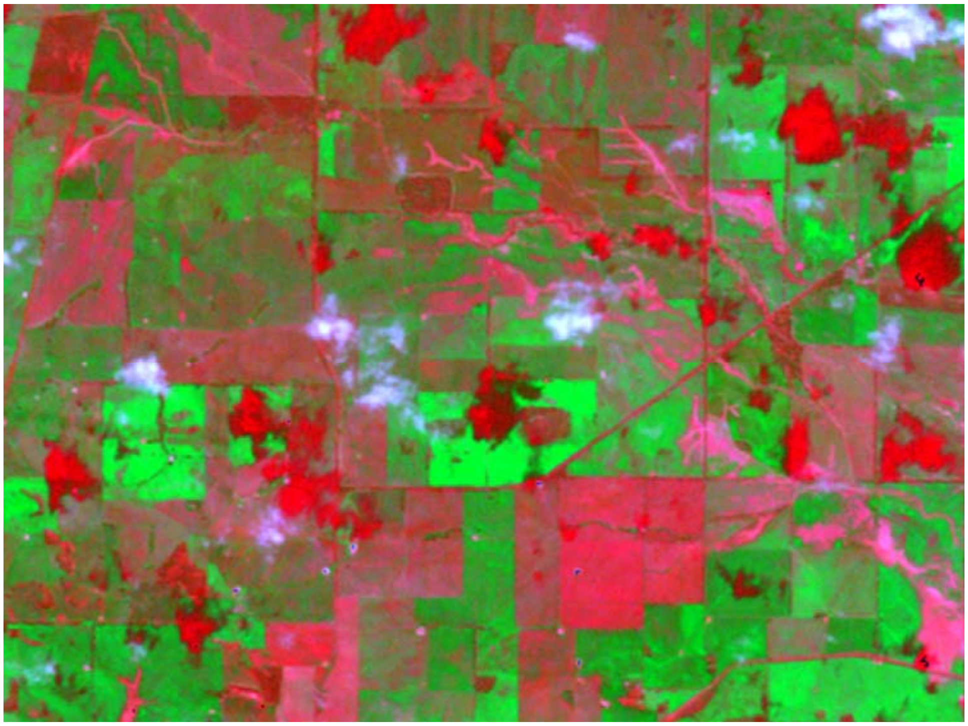
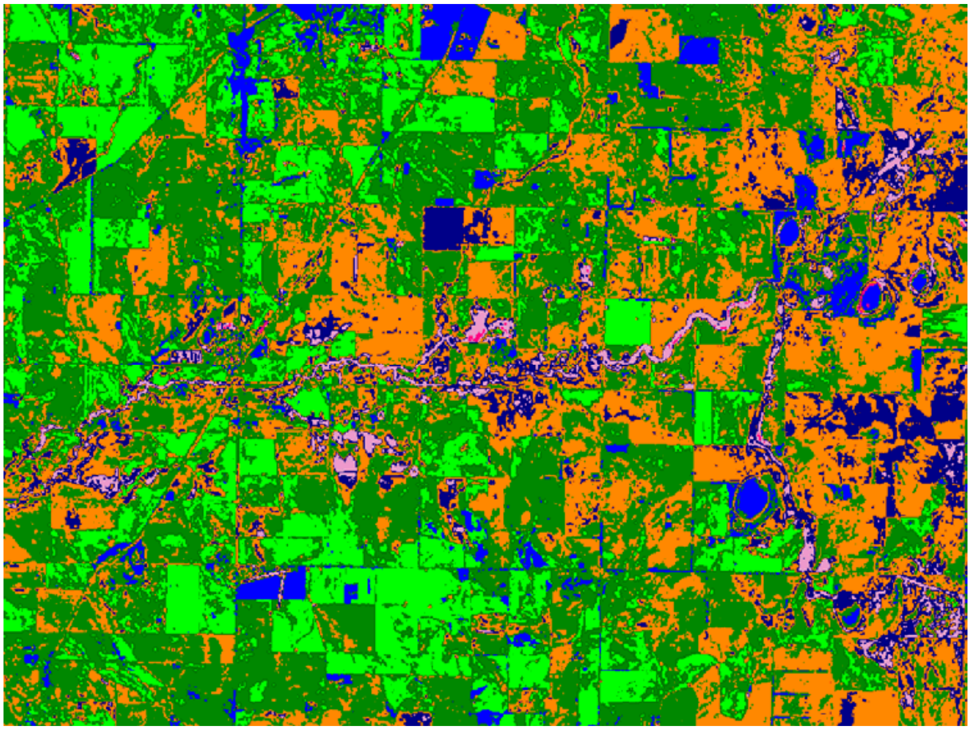


Figure 3-51 NDSI applied to Landsat 5 TM image of 21 July 2005 for Dumbleyung

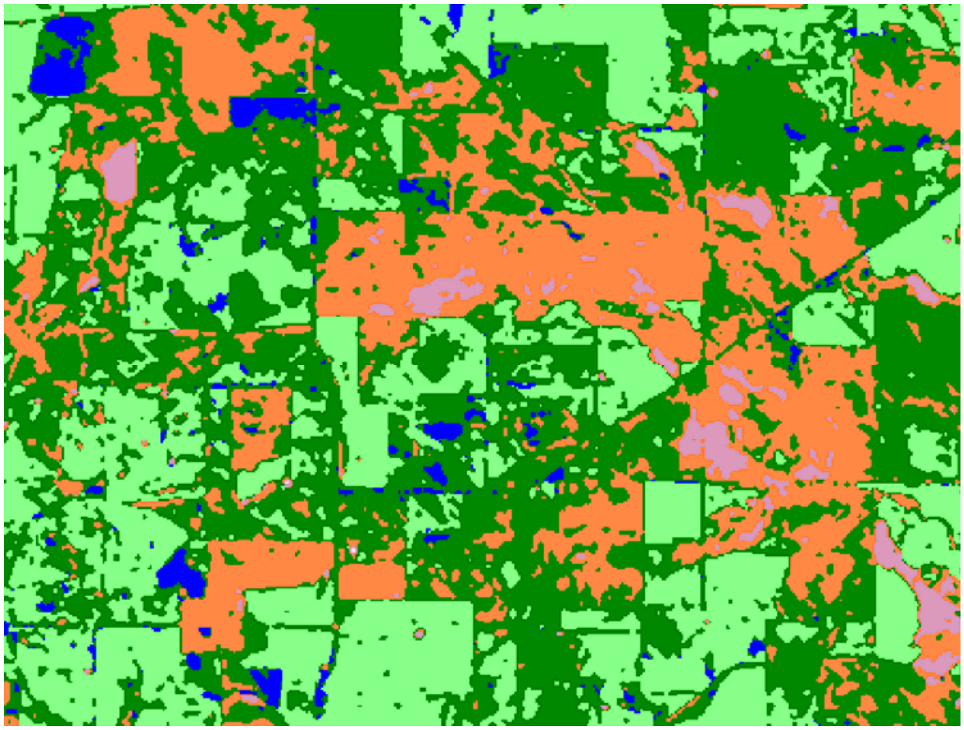
3. 4 Image Classification

Landsat 7 ETM+ image of 22 August 2002 for Narembeen was used for landcover classification using an unsupervised classification and ISOCLASS algorithm of ER Mapper which performs the clustering of the image data. An unsupervised classification was performed, as the complete site information was not available. A classification for 7 spectral classes of Water/Lakes/Remnant Vegetation, Grasses, Crops, Bare Degraded Soil, Waterlogged/Drains, Saline Soil and Salt Crust was done using Landsat 7 ETM+ bands 1,2,3,4,5,7. Unsupervised classification of Landsat 7 ETM+ image of 22 August 2002 for Narembeen in bands 7,4,1 is shown in Figure 3-51. The remnant vegetation in farmer's field in the north and south is classified as water in lakes in the east of the image. Unsupervised classification of Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung in bands 7,4,1 in Figure 3-52. All the roads in the image that are covered by trees have been classified as grasses and remnant vegetation in the image as water bodies. These errors can be removed by reclassification of the images. The composite images shown in sections 3.3.2, 3.3.6 and 3.3,7 and unsupervised classified images show that most of waterlogging and salinity problems are located along the drainage lines.



Class	Name	Color	
	All	black	Set color...
1	1: Water/Lakes/Remnant Veg.	blue	Set color...
2	2: Grasses	0,128,0	Set color...
3	3: Crops	128,255,128	Set color...
4	4: Bare Degraded Soil	255,128,64	Set color...
5	5: Waterlogged/Drains	208,151,191	Set color...
6	6: Saline Soil	255,128,192	Set color...
7	7: Salt Crust	255,0,128	Set color...

Figure 3-52 Unsupervised classification of Landsat 7 ETM+ image of 22 August 2002 for Narembeen in bands 7,4,1



Class	Name	Color	
	All	black	Set color...
1	1: Water/Lakes/Remnant Veg.	blue	Set color...
2	2: Grasses	0,128,0	Set color...
3	3: Crops	128,255,128	Set color...
4	4: Bare Degraded Soil	255,128,64	Set color...
5	5: Waterlogged/Drains	208,151,191	Set color...
6	6: Saline Soil	255,128,192	Set color...
7	7: Salt Crust	255,0,128	Set color...

Figure 3-53 Unsupervised classification of Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung in bands 7,4,1

3. 5 **Scatter Diagram**

The statistics of cloud free Landsat TM images from 1989 to 1996 for Kellerberin (111-082) are given in Appendix 3-1. The band 5 has the highest mean reflection and is highly correlated with band 3. The scattergrams of band 5 and band 3 were produced to show temporal and spatial change in saline, waterlogged and degraded land in Dumbleyung images of 1990, 1998 and 2002.

In ER Mapper, from View menu select Scattergrams and open Setup button. In Setup, band 5 is assigned to x-axis and band 3 to y-axis. Draw a box over a section of the scatterplot with x, y position of 65 and 68 for bottom left point, move 135 on x-axis and 100 on y-axis to draw the box. The graph will show the correlation between band 5 and band 3 of data from the same image. The scatter dots in the box are shaded red and the same pixels in the image also turn red. These red pixel in the image show the land degradation due to salinity and waterlogging. In 1990 image (Figure 3-54) land degradation in Dumbleyung was at the lowest and in 2002 image (Figure 3-56) the land degradation was at the highest even though the 2002 was a dry year. The increase in land degradation in Dumbleyung from 1990 to 1998 is show in Figure 3-55. The cloud free images for Dumbleyung deep drainage site after installation of drains were not available and no analyses could be performed to quantify the improvement in land degradation in deep drainage site.

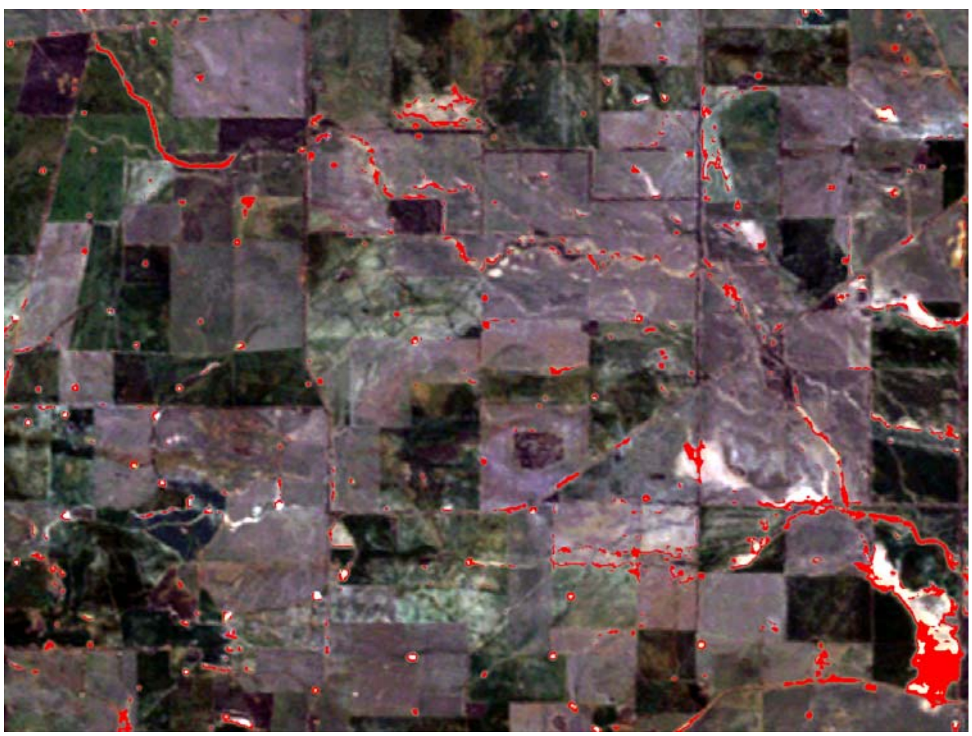


Figure 3-54 Land degradation shown in Landsat 5 TM image of 14 September 1990 for Dumbleyung

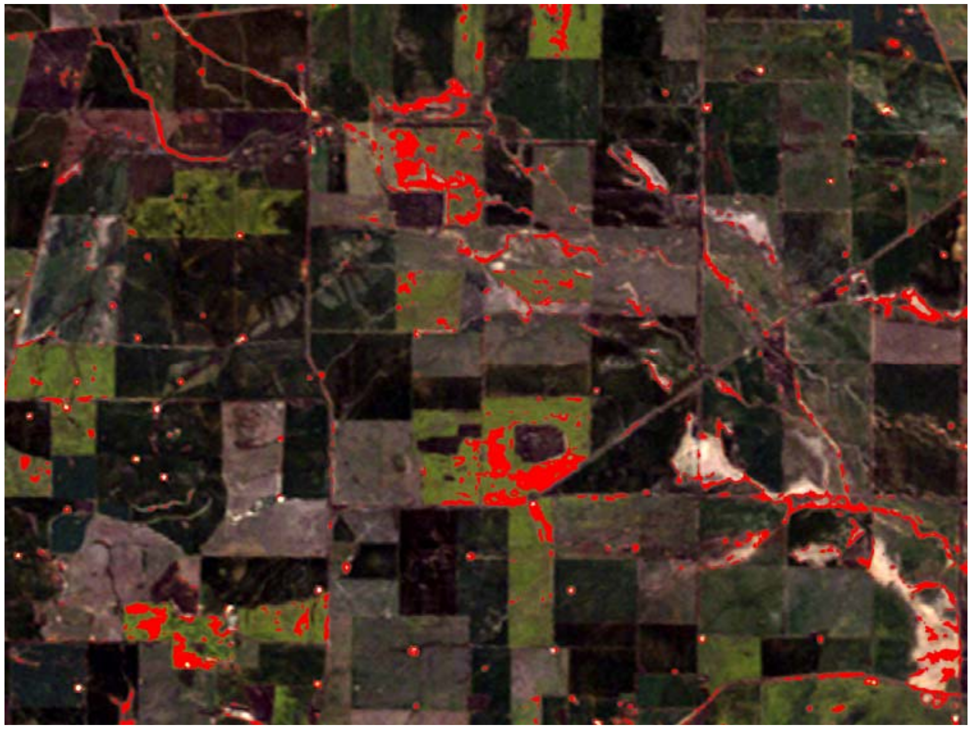


Figure 3-55 Land degradation shown in Landsat 5 TM image of 14 September 1998 for Dumbleyung

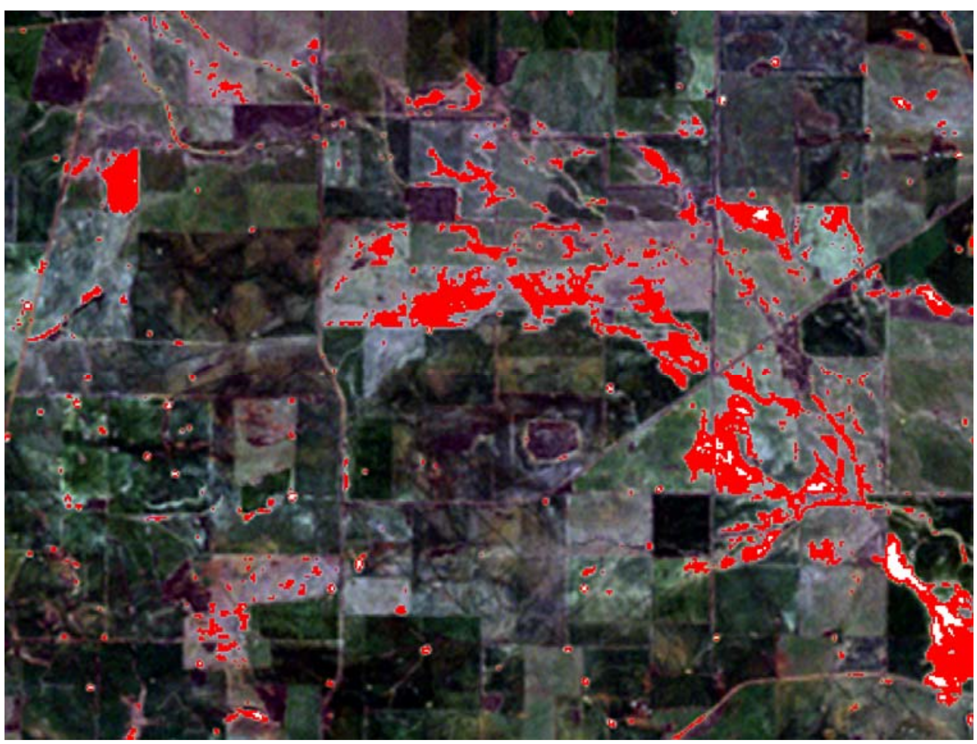


Figure 3-56 Land degradation shown in Landsat 7 ETM+ image of 22 August 2002 for Dumbleyung

3. 6 **Conclusions**

Remote sensing techniques and some indices were successfully used to predict risks of land degradation due to soil salinity and waterlogging in the study area. Time-sequenced Landsat TM satellite data and groundwater data were analysed to delineate areas where major changes in soil salinity, waterlogging and land degradation have taken place before and after engineering interventions of deep drains. In Dumbleyung saline, waterlogged and degraded areas have increased from 1990 to 1998, decreased in 2002 and slightly increased in 2005.

4 USE OF GIS IN MONITORING OF SURFACE WATER FLOWS IN WA

Water flows through the landscape and the condition of the land surface affects the flow and quality of water. Land condition can be characterised at any location by the type of land use, soils, climate and terrain conditions prevailing there. Land and water characteristics are connected. Land characteristics tend to be relatively fixed in time, and spatially extensive. Water characteristics vary much more in time but tend to be spatially concentrated, such as at points of measurement of streamflow or water quality. Erosion of the land pollutes the water with sediments, nutrients and pesticides.

A Digital Elevation Model (DEM) is an ordered array of numbers that represents the spatial distribution of elevations above some arbitrary datums in the landscape (Moore *et al*. 1993). A DEM is prepared from contour data or stereo-satellite data using geographical information system (GIS). Classification of the catchments to different hydrogeomorphic units can be performed using GIS techniques (Salama *al et*., 1996; 1997b; 1999a). A high-quality DEM produced by Land Monitor that can be used to delineate stream network lines, drainage lines and hydrogeomorphic parameters required for the characterisation of the area. Most of the salinity of soil is associated with shallow water levels in the lower areas of the catchment and salinity decrease with increase in water level depth with increasing altitude. In the confined aquifers there is an inverse relationship between water level and aquifer depth (Salama *et al*., 1996; 1997b; 1999a). In this chapter a methodology for generating a stream network using a DEM and digitising drains or streams from topographic maps and aerial photographs will be developed and will be used for data analysis.

4. 1 Surface Water Hydrology

Surface water management can be performed if meteorological and hydrologic data of a catchment is available to calculate the flow accumulation and direction, catchment boundary delineation, and stream networks for planning the drainage design and to manage the salinity, flood, and waterlogging problems in southwest of Western Australia. The size, shape and topography of a surface determine how water will flow across it. Topographic features of slopes of upland areas and channels, extent of flatness of catchment area or depressed areas without surface outlets affect rates and volumes of runoff.

Most of the commercially available GIS packages have routines and commands to calculate drainage networks. Caccetta (1997) processed DEM data with GRASS routine r.watershed and found water accumulation algorithm produced drainage network that was within 600 m of the true drainage network. Chow *et al*., (1988) defined hydrological process of surface water flow as when the soil moisture capacity is exceeded; the excess rainfall becomes overland flow until it is drained in one of the catchment channels.

In order to determine where the water is coming from and where it is going in a catchment one has to delineate catchment areas and streamlines in it. Surface water hydrology analysis in the following section is conducted using ArcView GIS tools. The spatial analyst ArcView extension is also required for conducting this work. A high-quality DEM of Narembeen in Western Australia, produced by Land Monitor Project, is opened in ArcView GIS (Figure 4-1). This DEM was formed by smoothing the Landmonitor DEM (Caccetta, 1999) and was resampled from 10 m pixel size to 25 m. A DEM grid contains both sinks and peaks which may be due to naturally occurring features. A sink is surrounded by higher elevation area and acts as internal drainage area. Water flowing into a sink will be trapped and can artificially terminate stream flow. It is important to identify and fill sinks in a DEM grid so that flow can be routed to compute the streamlines and catchment boundaries. Filling sinks is an iterative process in which sink values are changed to lowest neighbouring elevation cell values. Hydro extension was loaded in the extensions and DEM theme was made active. Fill sinks option in Hydro extension was used from the menu to get another grid with sinks filled.

To find out the areas where sinks were filled, height differences between the cells of the two grids were calculated using Map calculator in ArcView GIS. Figure 4-2 shows the differences between the cells of the two grids which are mostly in valley floors and lakes.

Surface slopes from the DEM can be calculated which can be used in calculating water velocity in channels and selecting different conservation practices in the catchments such as banks, spoon and W-drains, reverse-bank seepage interceptor drains and shallow and deep drainage drains for managing surface and groundwater.

Filled DEM grid of Narembeen was selected as an active theme and Derive Slope from the Surface menu was used to compute another grid which has values of slopes in degrees (Figure 4-3).

Flow directions are created from a DEM grid that will be used to calculate flow accumulation. Flow directions are calculated from the direction of flow for each cell to its steepest downslope cell from the eight neighbouring cells. Flow directions are coded as follows:

1 - East

2 - Southeast

4 - South

8 - Southwest

16 - West

32 - Northwest

64 - North

128 - Northeast

Narembeen Filled DEM was made an active theme and Flow Direction command from Hydro menu was used to calculate flow directions. Flow accumulation calculates the value of flow from one cell to another considering all uphill cells. Flow accumulation is an indirect way of measuring catchment or drainage areas in units of grid cells. Flow accumulation is calculated by making Flow Direction grid an active theme and use Flow Accumulation command from the Hydro menu.

In order to find Streamline Network, Flow Accumulation grid is made an active theme and Stream Network as Line Shape from the Hydro menu is selected, enter 6,000 for the minimum number of cells for a stream network and select Flow accumulation is a measure of the drainage area in units of grid cells. Flow Directions theme from the list when prompted. Flow Accumulation calculated 6,000 points in Figure 4-5 for Narembeen was overlayed on an aerial orthophoto of the area in Figure 4-6. The calculated stream network was not matching with the aerial orthophoto. The minimum number of cells for calculating stream network was increased from 6,000 to 6,500 but still it was not matching with the aerial orthophoto stream network (Figure 4-7). The best result of stream network calculations was achieved with minimum 7,000 numbers of points and the calculated stream network was fully matching with the orthophoto of stream network (Figure 4-8). Flow

Accumulation calculated with 7,000 points in Narembeen catchment can be used to find the creeks, streams and drainage lines in an area using DEM.

To find the subcatchments in the Narembeen DEM grid, Flow Accumulation theme was made an active theme and Watershed command was used from the Hydro menu to select size of the catchment for delineating subcatchment. The minimum number of 7,000 cells for a watershed and Flow direction theme was selected when prompted for the direction grid theme. Flow accumulation calculated from 7,000 points for Narembeen is given in Figure 3-9. Figure 3-10 shows the subcatchments in the Narembeen area. The risk of salinity from rising water table or surface water runoff can be calculated from a DEM. A DEM classification of Narembeen Filled grid resulted in three classes; Red <250 m AHD showing a high risk of salinity, Blue =>250 m AHD and <350 m AHD showing a medium risk of salinity and Yellow>350 m AHD showing a low risk of salinity (Figure 3-11).

Similarly, flow accumulation was calculated for Dumbleyung from 7000 minimum points (Figure 3-12). Flow accumulation calculated from 7,000 points overlayed on an orthophoto of Dumbleyung produced the best match of flow network calculated and flownetwork in an orthophoto of Dumbleyung (Figure 3-13). These procedures of calculations of flow accumulations, flow networks and catchment slopes from DEM can be applied in any catchment of Wheatbelt of Western Australia.

If the catchments factors are known then the Universal Soil Loss Equation (USLE) given in Equation 4-1 can be used to estimate average soil loss per year in a catchment described by Wischmeier and Smith (1978).

$$A = RKLSCP \tag{4-1}$$

Where A = average annual soil loss (Mg ha^{-1})

R = rainfall and runoff erosivity index for a given location

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C= cover and management factor

P = conservation or support practice factor

In order to get erosivity index ‘R’ the erosion index (EI) for a given storm that is a product of the kinetic energy of the falling raindrops and its maximum 30 minute intensity is calculated. The sum of these EI values over a year divided by 100 give the annual ‘R’ factor. Fangmeier *et al*., (2006) have also reviewed the latest erosion prediction methods that include a revised version of USLE known as RUSLE and WEPP MODEL. All the parameters of USLE are explained and the equations to derive these parameters are given by Fangmeier *et al*., (2006).

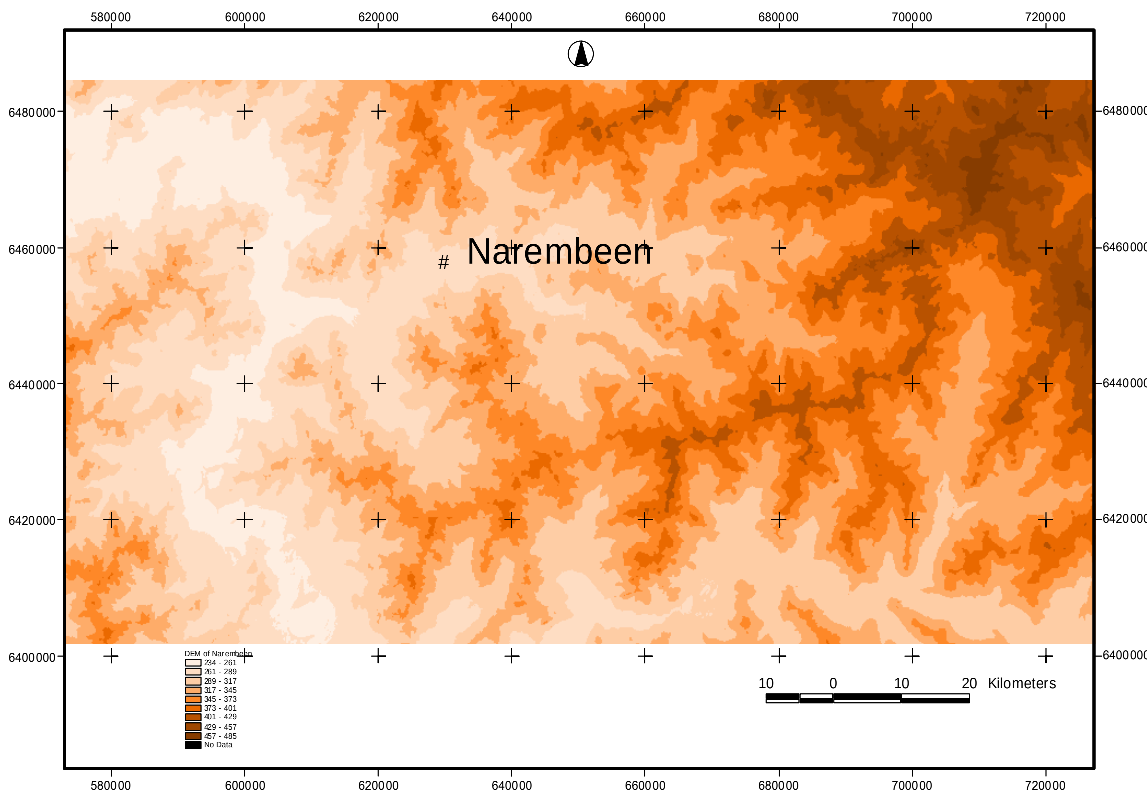


Figure 4-1 A Digital Elevation Model (DEM) of Narembeen in Western Australia

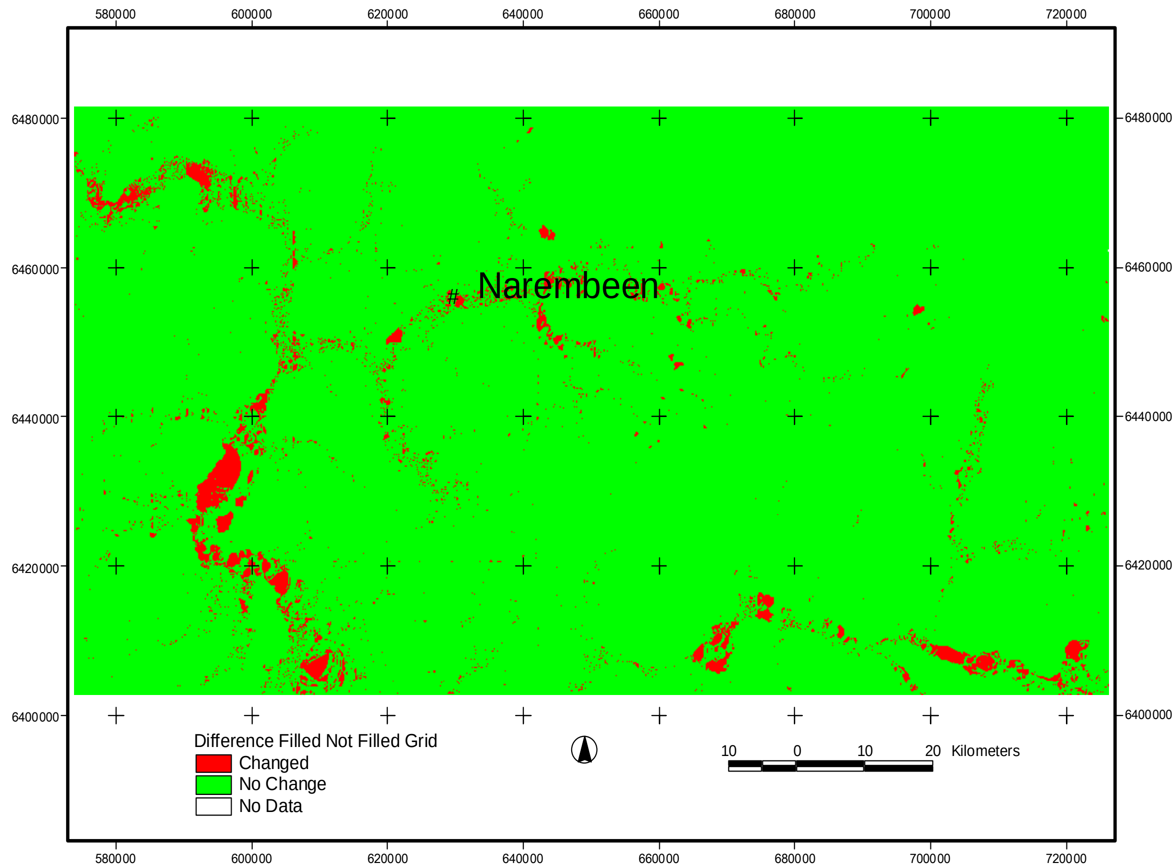


Figure 4-2 Difference of the cells of Filled and Not Filled grids for Narembeen

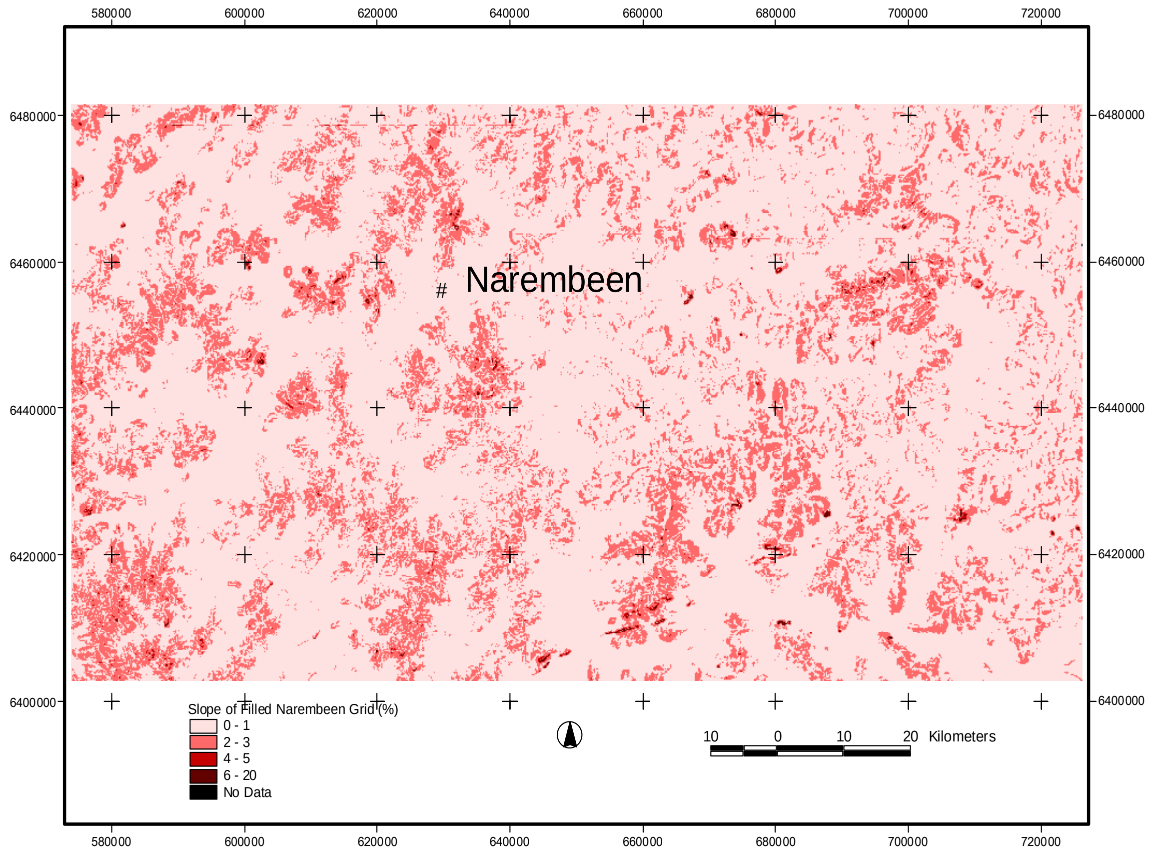


Figure 4-3 Slopes of Filled DEM grid of Narembeen in degrees

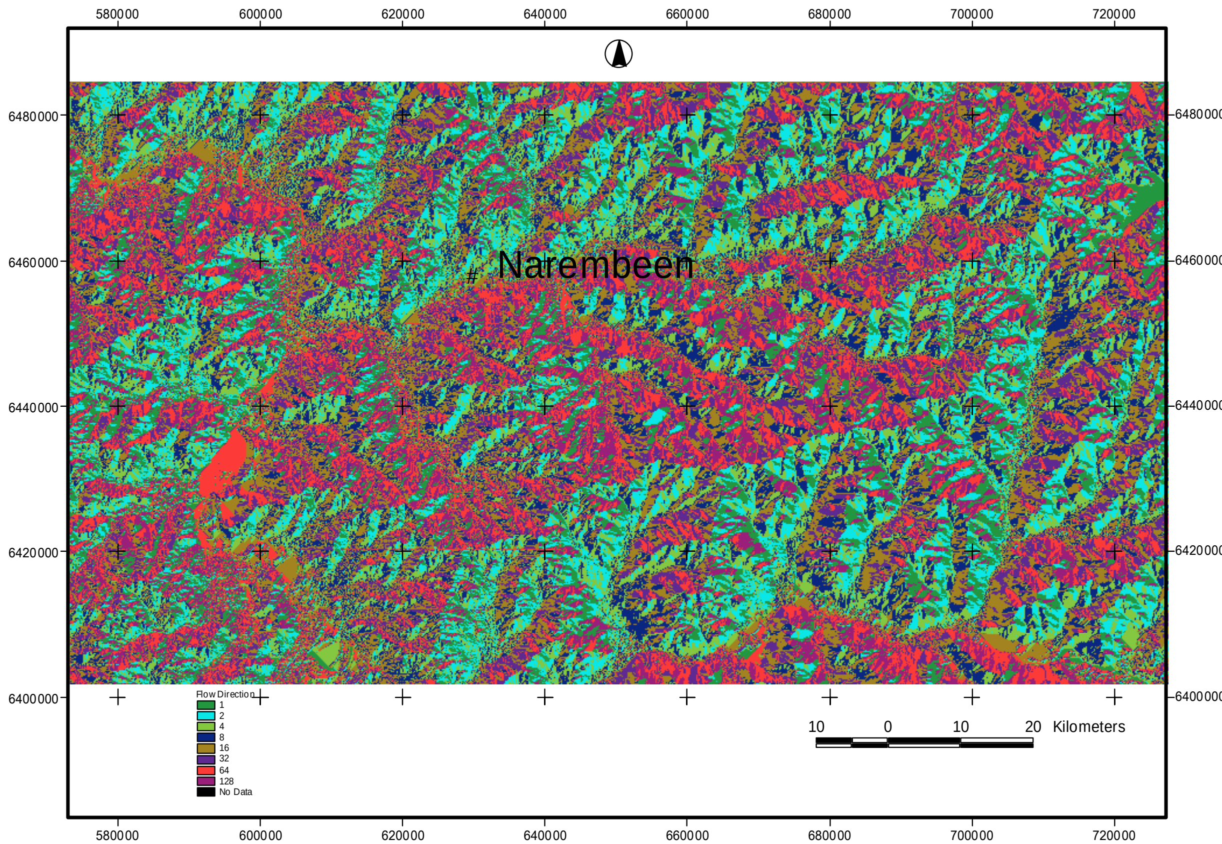


Figure 4-4 Flow directions of Filled DEM grid of Narembeen

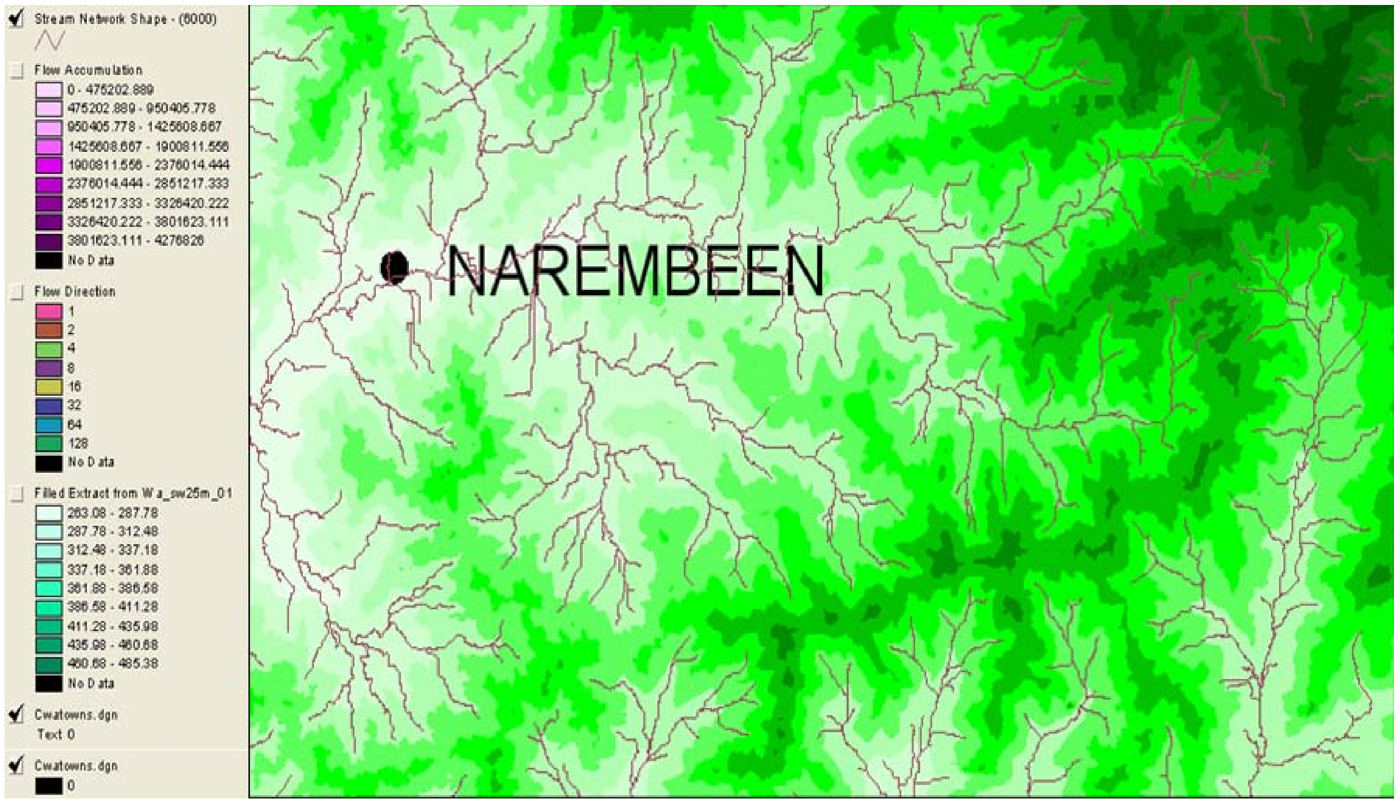


Figure 4-5 Flow accumulation of Filled DEM grid of Narembeen calculated from 6000 points

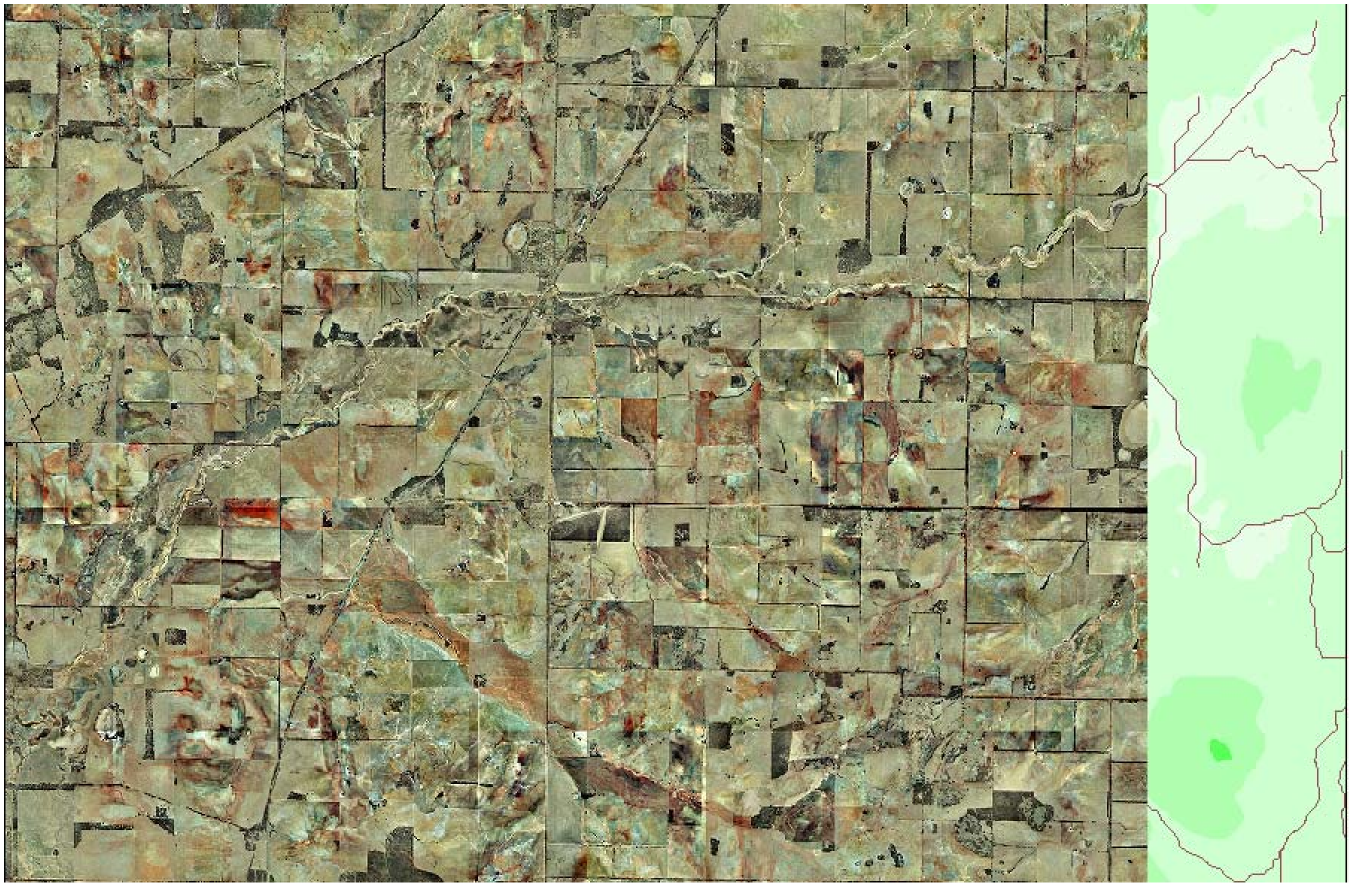


Figure 4-6 Flow accumulation calculated from 6000 points overlayed on an orthophoto of Narembeen

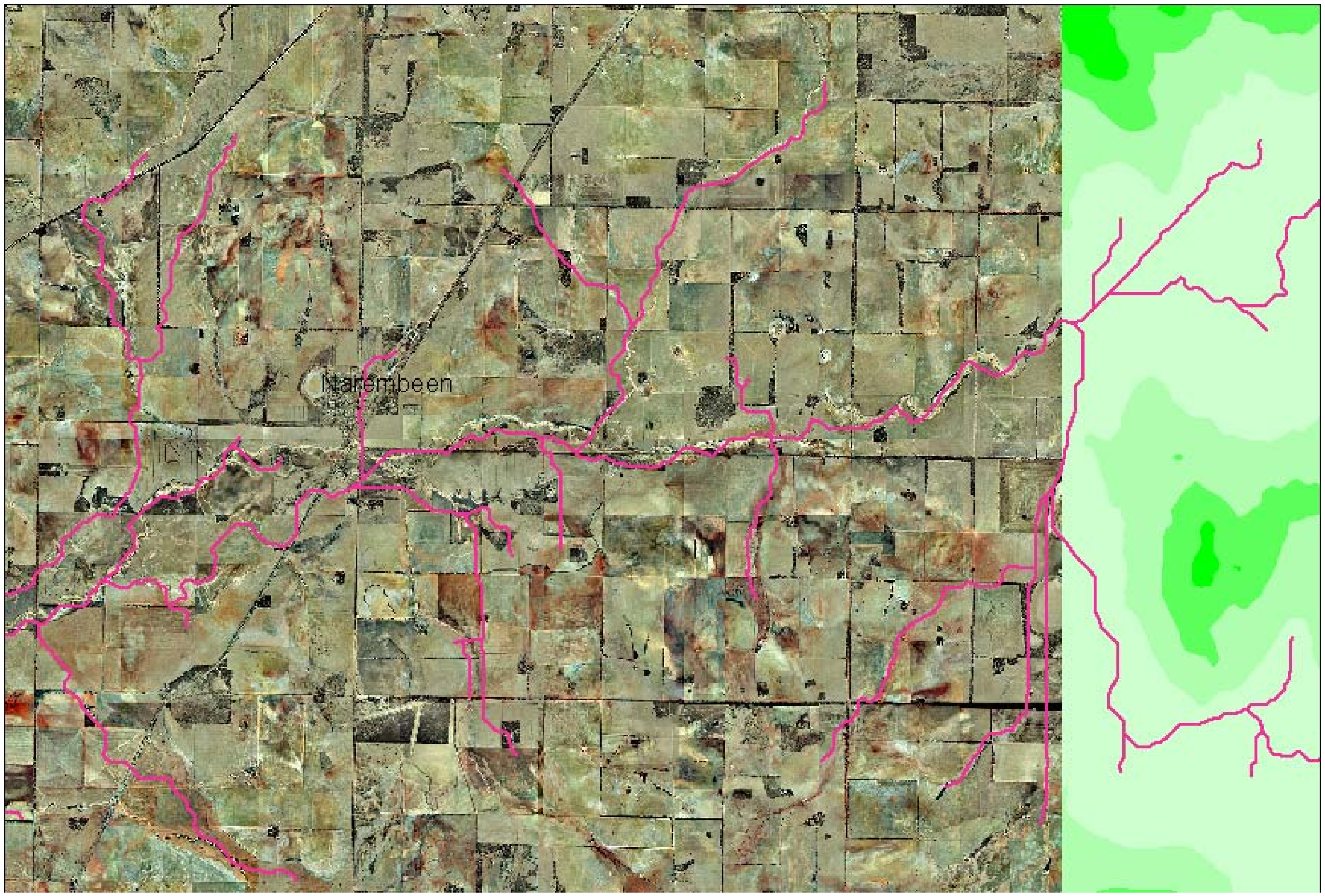


Figure 4-7	Flow accumulation calculated from 6500 points overlayed on an orthophoto of Narembeen

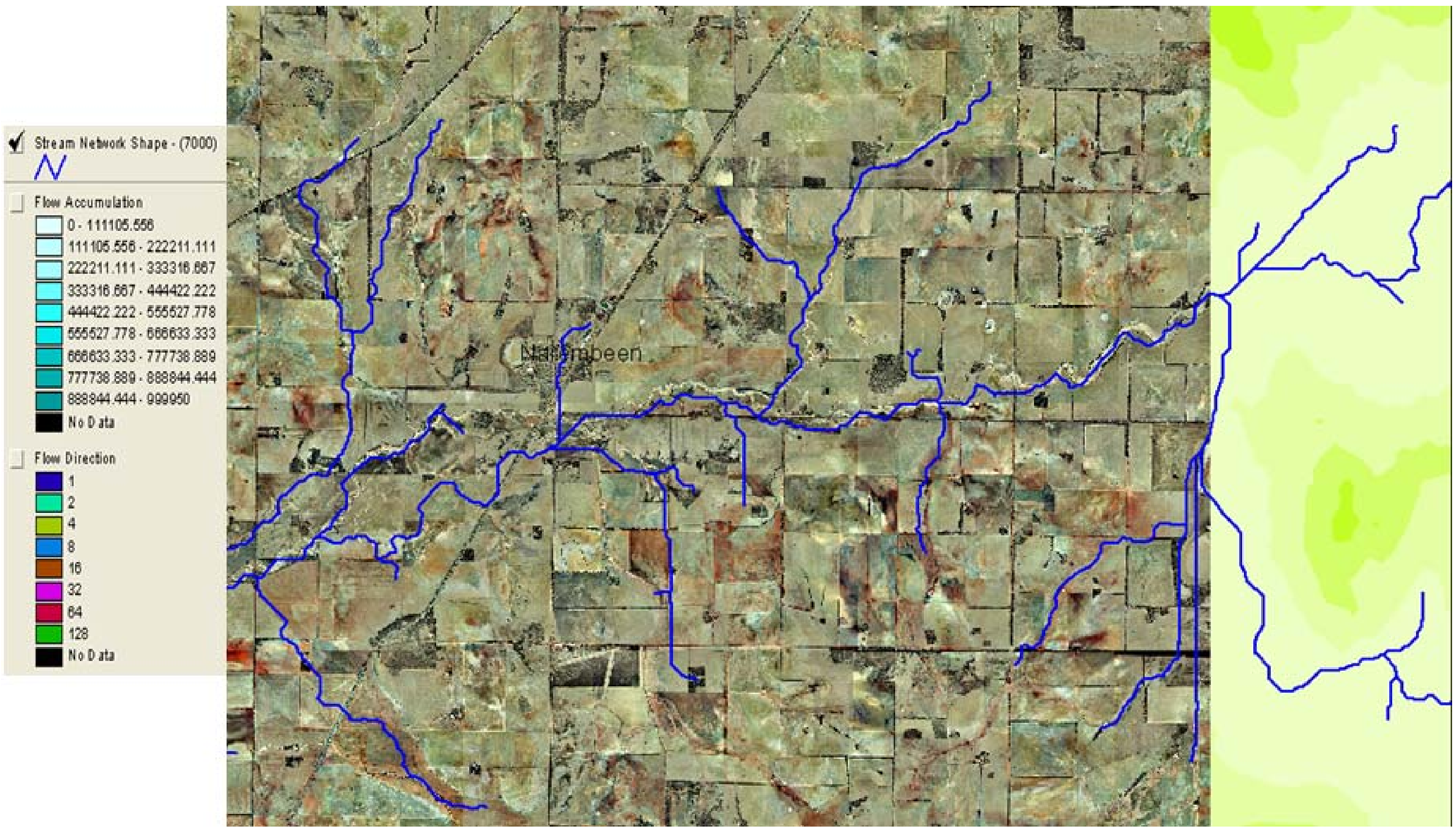
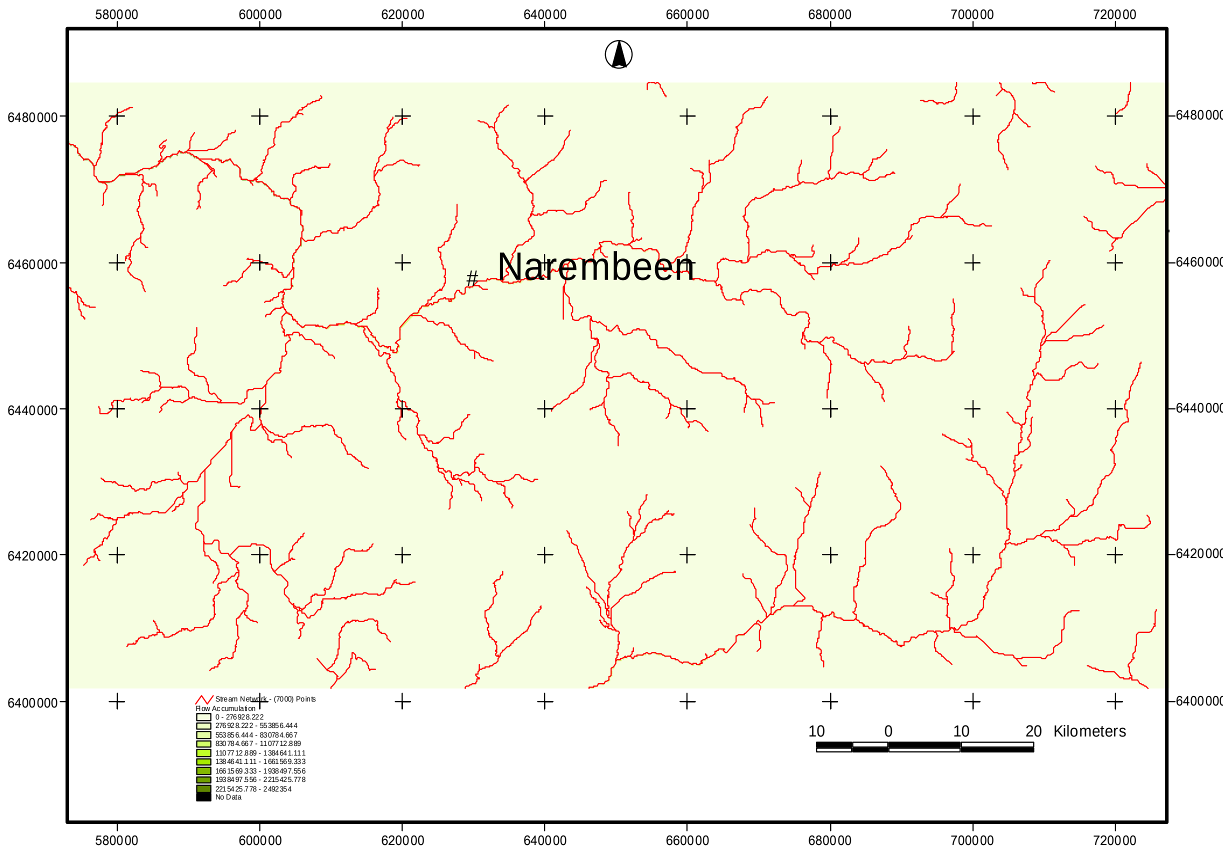


Figure 4-8 Flow accumulation calculated from 7000 points overlayed on an orthophoto of Narembeen



4-9 Flow accumulation calculated from 7000 points for Narembeen

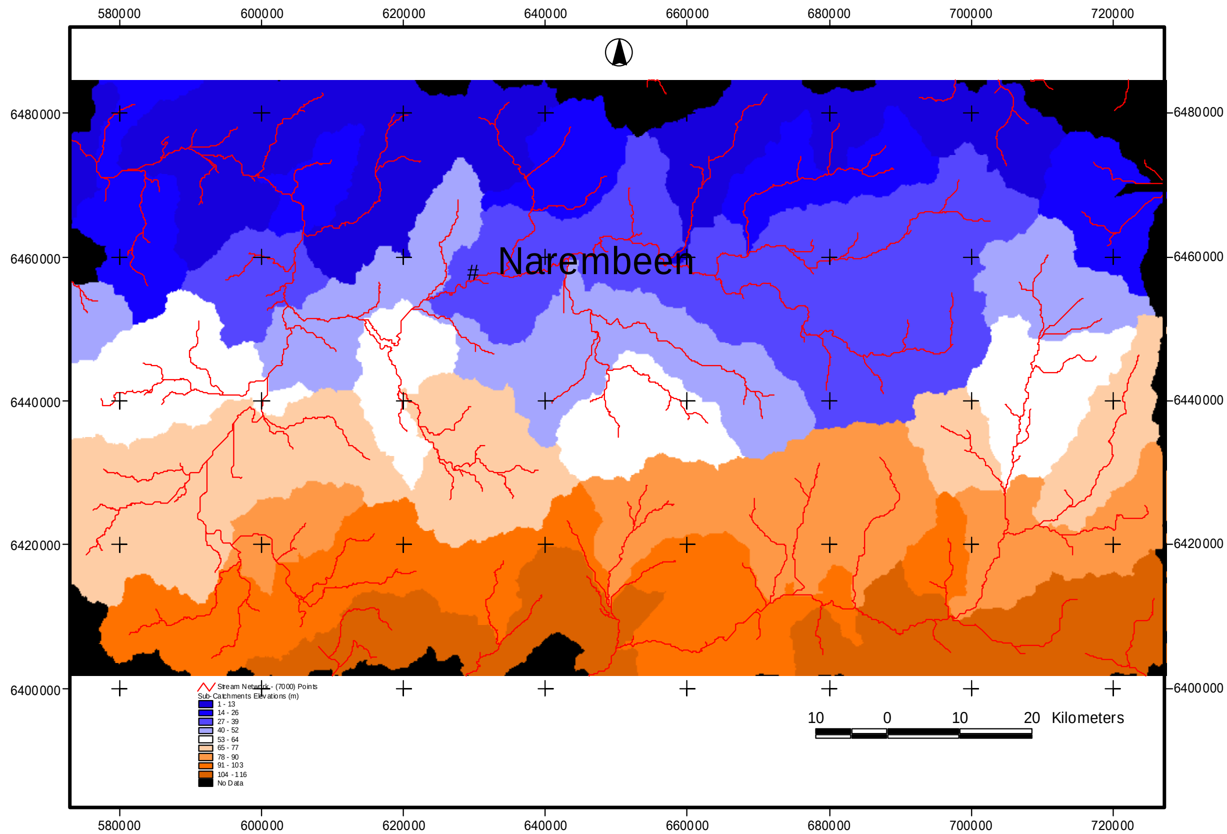


Figure 4-10 The subcatchments calculated for Narembeen area

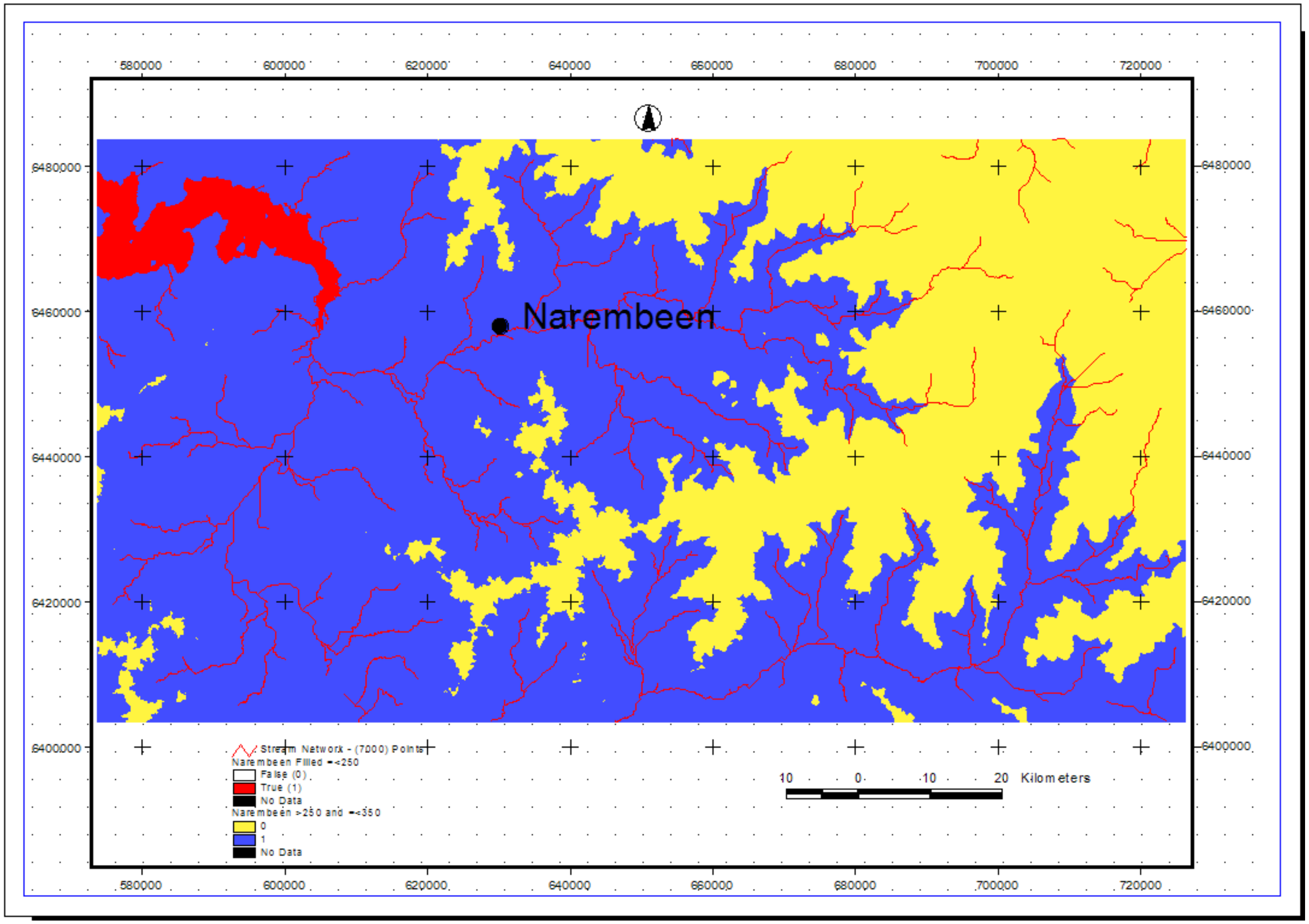


Figure 4-11 DEM classification of Narembeen Filled grid, Red <250 m, Blue =>250 m and <350 m Yellow>350 m

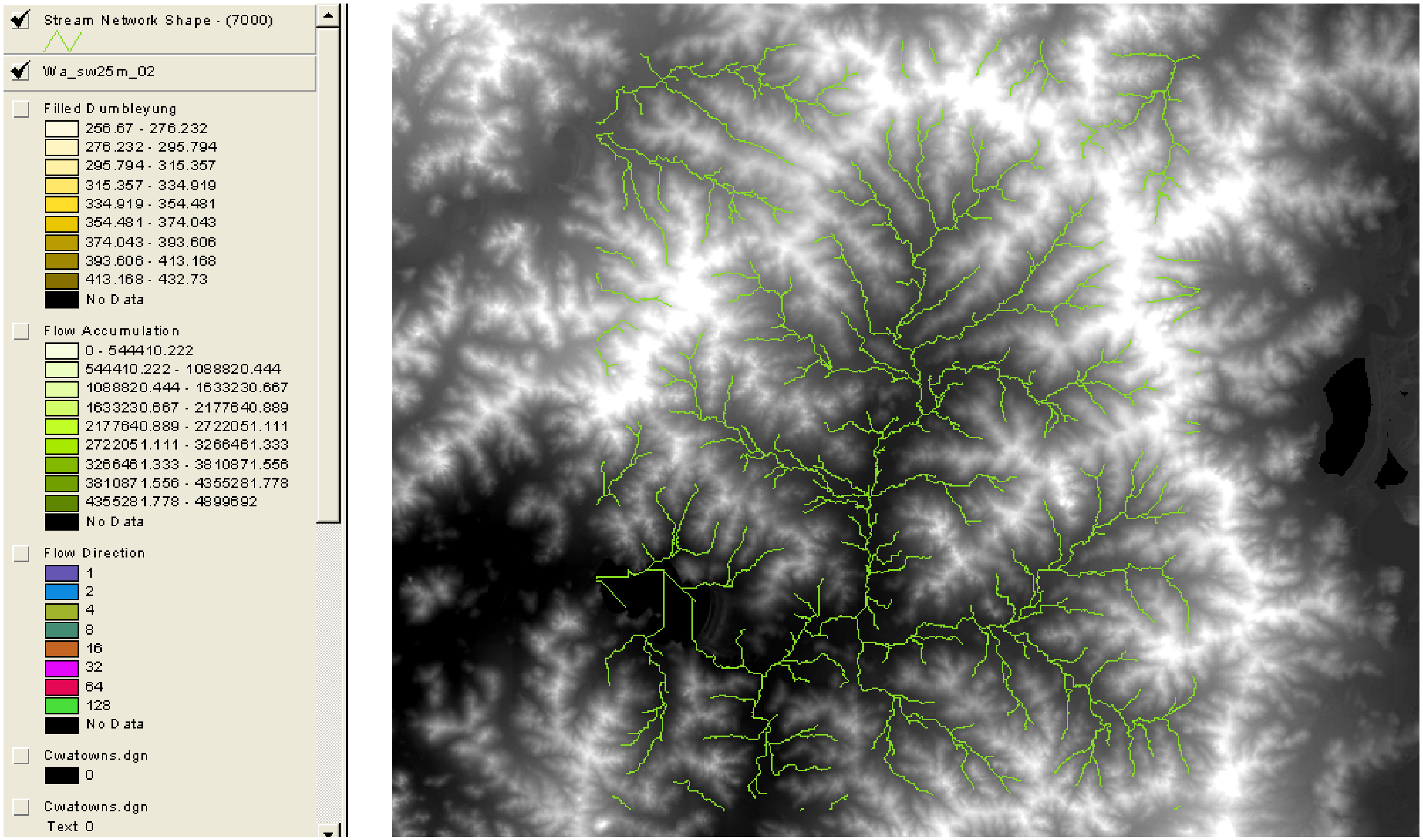


Figure 4-12 Flow accumulation calculated from 7000 points for Dumbleyung

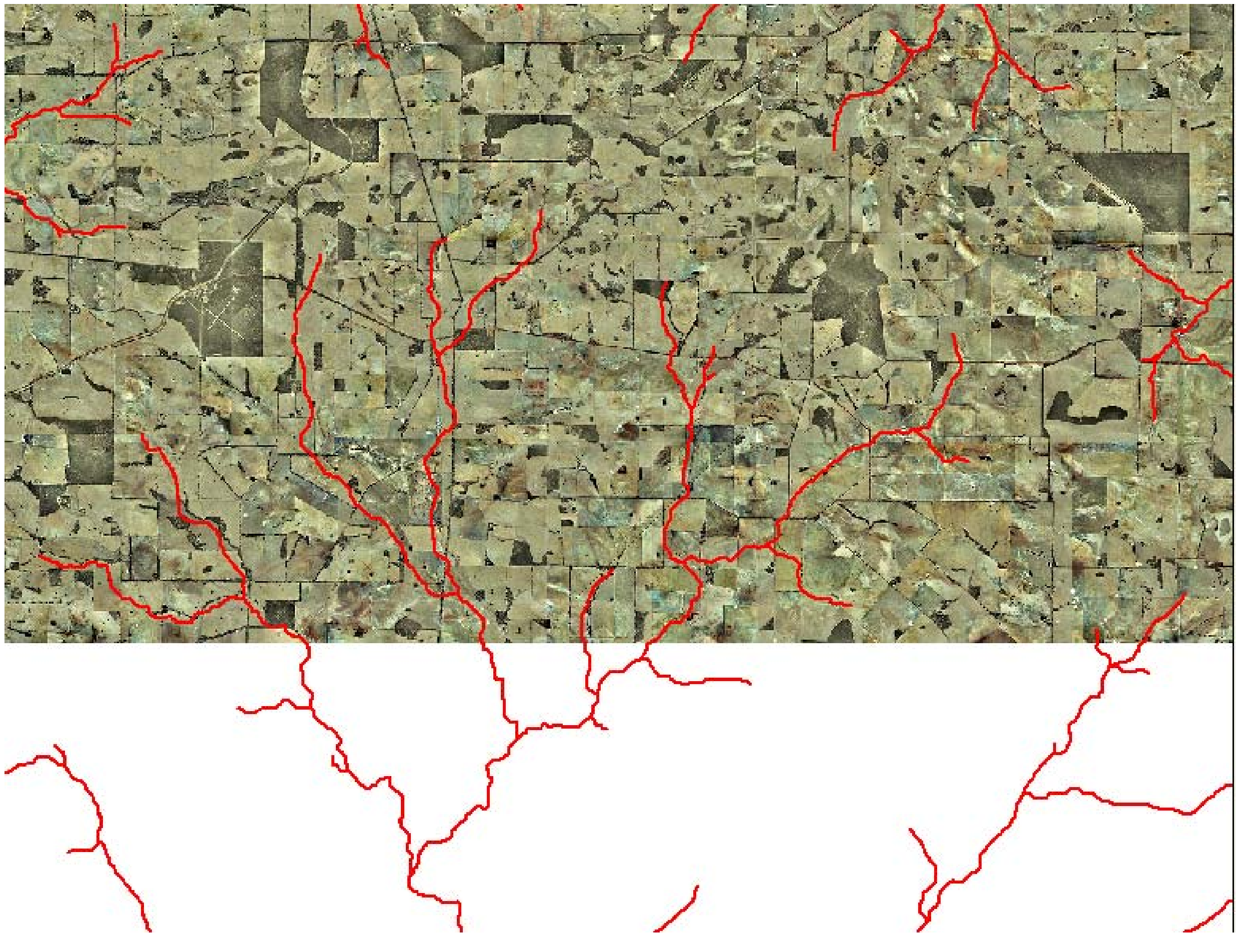


Figure 4-13 Flow accumulation calculated from 7000 points overlayed on an orthophoto of Dumbleyung

4. 2 **Use of GIS in Monitoring Pollutants in Torbay Catchment**

4.2.1 Torbay Catchment

The Torbay catchment is located in between cities of Demark and Albany and situated at 26 kilometres west of Albany on the south coast of Western Australia. There are more than 70 kilometres of excavated drains in the Torbay Catchment, excluding feeder drains constructed on individual properties and over 180 kilometres of natural waterways within the catchment.

4.2.2 Order Classification

Excess water from surface runoff or baseflow from groundwater makes its way to minor rills, streams and rivers in a catchment which flows in a pattern and called a stream (drainage) network. The streams and drains in a catchment can be digitised from topographic base map or aerial photographs. This network can be described by stream order, number and length. Stream order is a numbering system that describes the position of a particular stream in the hierarchy of tributaries in a catchment. The order of a stream can provide clues about other stream characteristics, including its longitudinal zone and the relative size and depth of its channel.

First-order streams are headwater channels with no definite upstream tributaries. When two first-order streams meet, a second-order stream is formed. A third-order stream is created when two second-order streams combine. The process of ordering the stream channels continues to the outlet of the catchment. Strahler (1952) modified the Horton ordering system and now it is widely used. Strahler's system of stream classification has been used to show stream order (1st, 2nd, 3rd etc.) in Figure 4-14.

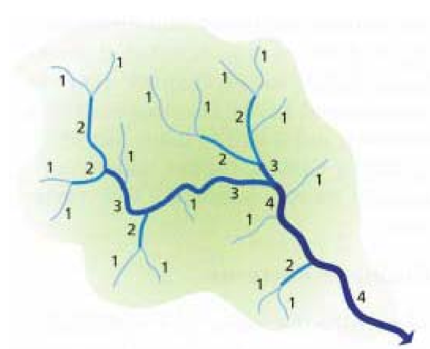


Figure 4-14 Strahler’s system of drains or streams classification
(http://www.epa.gov/watertrain/stream/s29.jpg)

A digitiser tablet onto which a paper map is placed is used for digitising the streams and drains with the help of a digitising puck. In ArcView GIS, on-screen digitising can be done with the mouse which can be used to move an on-screen cursor and place points, lines and polygons. In ArcView GIS open a New Theme and set the feature as 'line' and select the Draw Line tool to start digitising the stream or drain line on a digital topographic map or an aerial photograph. The size and colour of the line can be changed from legend editor in ArcView GIS. Ecotones & Associate (2002) provided GIS data for Torbay catchment during a 2-day training programme.

Streams or drains in Albany, Denmark and Mount Barker area were digitised and are presented in Figure 4-15. Streams or drains in Albany, Denmark and Mount Barker area overlayed on a topographic topographic base map of Scale 1:250,000 in order of, 1,2,3,4 and more than or equal to 5 are presented in Figure 4-16.

In ArcView GIS, make the stream order theme active and from Theme button go to Select by Theme and type Intersect in Select Feature of the Active Theme window and Stream Order in the Selected Feature window and press NEW Start button. Open the table of Stream Order Theme and click on the Summarise Tool to open the Summary Table Definition dialogue. In Summary Table Definition dialogue, select Length in field and Sum in Summarise by windows and press Add to get the expression Sum-Length which will calculate the stream counts and stream lengths in Albany, Denmark and Mount Barker area (Table 4-1). The streams or drains which start and end nowhere are counted as 0 orders. There are 2,257 streams and drains in first order and total length of streams and drains is 2,486 km.

Table 4-1 Length of streams and Drains in Albany, Denmark and Mount Barker

Stream Order	Count	Length of Streams and Drains (m)
0	263	160,152
1	2257	2,485,843
2	519	940,139
3	126	491,965
4	34	268,414
5	14	149,824
6	3	34,014
7	1	80,303

If stream or drain lengths are required only in Torbay catchment, make the stream order theme active and from Theme button go to Select by Theme and type Intersect in Select Feature of the Active Theme window and Torbay catchment in the Selected Feature window and press NEW Start button. The streams and drains in Torbay catchment are shown in yellow colour (Figure 4-18). Follow the procedure to calculate the stream counts and stream lengths from previous section in Torbay catchment (Table 4-2). This information is useful in determining the length of fencing required for segments of any order of streams or drains, location of stream crossings and location of gauging stations to determine flow rates and monitor pollutants in streams and drains.

Table 4-2 Length of streams and drains in Torbay catchment

Stream Order	Count	Sum of Length of Drains (m)
0	156	85,857
1	253	192,006
2	62	96,540
3	17	47,970
4	6	17,650
5	3	10,108

4.2.3 Soil Classification

Soil test have been conducted for 534 locations in Torbay catchment (Figure 4-19). In ArcView GIS, Query Builder dialogue has been used to analyse the soil data in Torbay catchment (Table 4-3). In Query Builder dialogue an expression is built to find the answer to any query. As an example, to find any soil test that are 'Brown Sandy Loams <30 cm deep over clay or gravel' an expression in Query Builder will be entered as follows:

([Soil-type] = "Brown Sandy Loams < 30cm deep over clay or gravel")

The majority of the soils are sandy with low moisture holding capacities.

Table 4-3 Soil types in Torbay catchment

Soil Types	No. of Records
Peat	7
Peaty sands	43
Very gravelly <30 cm	24
Grey and brown sands <30 cm	4
Grey sands <30 cm deep over gravel	75
Grey sands <30 cm deep over clay	25
Grey sands 30-75 cm deep over gravel or clay	99
Gravelly sands (10%) < 30 cm deep over gravel or clay	29
Dry grey sands >75 cm deep	98
Dark grey sands <30 cm over paler sands	54
Clay or sandy clays	6
Brown sandy loams > 30 cm deep over clay or gravel	24
Brown sandy loams < 30 cm deep over clay or gravel	46
Total	534

4.2.4 Pollutant Load in Torbay Catchment

The possibility of combining both point and non-point pollution sources overlaid on spatial data with intake and the discharge areas derived from a catchment may be quite effective in water-related environmental studies and planning. The relationships between land and water resources can be characterized by coefficients such as a runoff coefficient C which specifies the proportion of rainfall that becomes runoff. Water quality in a catchment is characterized by the Expected Mean Concentration, (EMC), which is the ratio of pollution load to flow during a runoff period. Pollutant loads are found by taking the product of the EMC and the streamflow rate. The sediment yield of a catchment is measured by the erosion rate and it can be calculated by estimating sediment load in a river and dividing it by the upstream drainage area.

Reactive Iron fixes Phosphorous (P) in the soil. Reactive Iron in soil samples have been plotted using ArcView GIS in Torbay catchment. A graduated symbol classification was used to display a range of values of Reactive Iron (Figures 4-20).

The highest concentration of Reactive Iron in soil samples with a range from 2,001 to 3,500 mg L^{-1} is in the north-west of Torbay catchment that can flow into Torbay Inlet through 1st order streams. Total P in soil samples in Torbay catchment are presented in Figure 4-21. The highest concentration of P in soil samples with a range from

7,001 to 1,000 mg L $^{-1}$ and from 1,001 to 4,000 mg L $^{-1}$ is in the west and east close to Torbay Inlet. If reactive iron is available in the soil then there are less chances of P flowing into streams and drains through surface flows. Runoff and soil erosion from agricultural lands are major causes of phosphorus pollution of surface waters. Phosphorus in soil is held tightly by soil particles and does not contaminate the groundwater.

NH_4 in soil samples pose a problem of Nitrogen (N) leaching in groundwater and making its way to Torbay streams and drains and polluting the Torbay inlet. The highest concentration of NH_4 in soil samples with a range from 31 to 40 mg L $^{-1}$ and from 41 to 80 mg L $^{-1}$ is in the south of Torbay catchment close to Torbay Inlet. (Figure 4-22). Nitrate leaching is the major pathway movement with percolating water to groundwater (permanent or transient) substantial groundwater emerges to surface as springs & seeps artificial drains in agricultural fields directly move leached nitrate to surface waters.

The median Total Nitrogen (TN) concentration from 1997 to 2005 was 1.8 mg L $^{-1}$ with annual medians ranging between 1.05 mg L $^{-1}$ (2000) and 2.00 mg L $^{-1}$ (1997) in Torbay Inlet. The median Total Phosphorus concentration was 0.460 mg L $^{-1}$ with annual medians ranging between 0.380 mg L $^{-1}$ (2000) and 0.550 mg L $^{-1}$ (1997) during 1997-2005 monitoring period.

The targets have been set for TN and TP for Torbay catchment for 2020. The median nutrient concentrations (mg L^{-1}) discharged from the sub-catchments should meet TN/TP target of 1.80 / 0.110 mg L $^{-1}$ in 2020.

The methodologies for generating stream network using DEMs and digitising drains or streams from topographic maps and aerial photographs have been developed and management of pollutants in the soil and water is discussed in detail in Chapter 6 of the thesis.

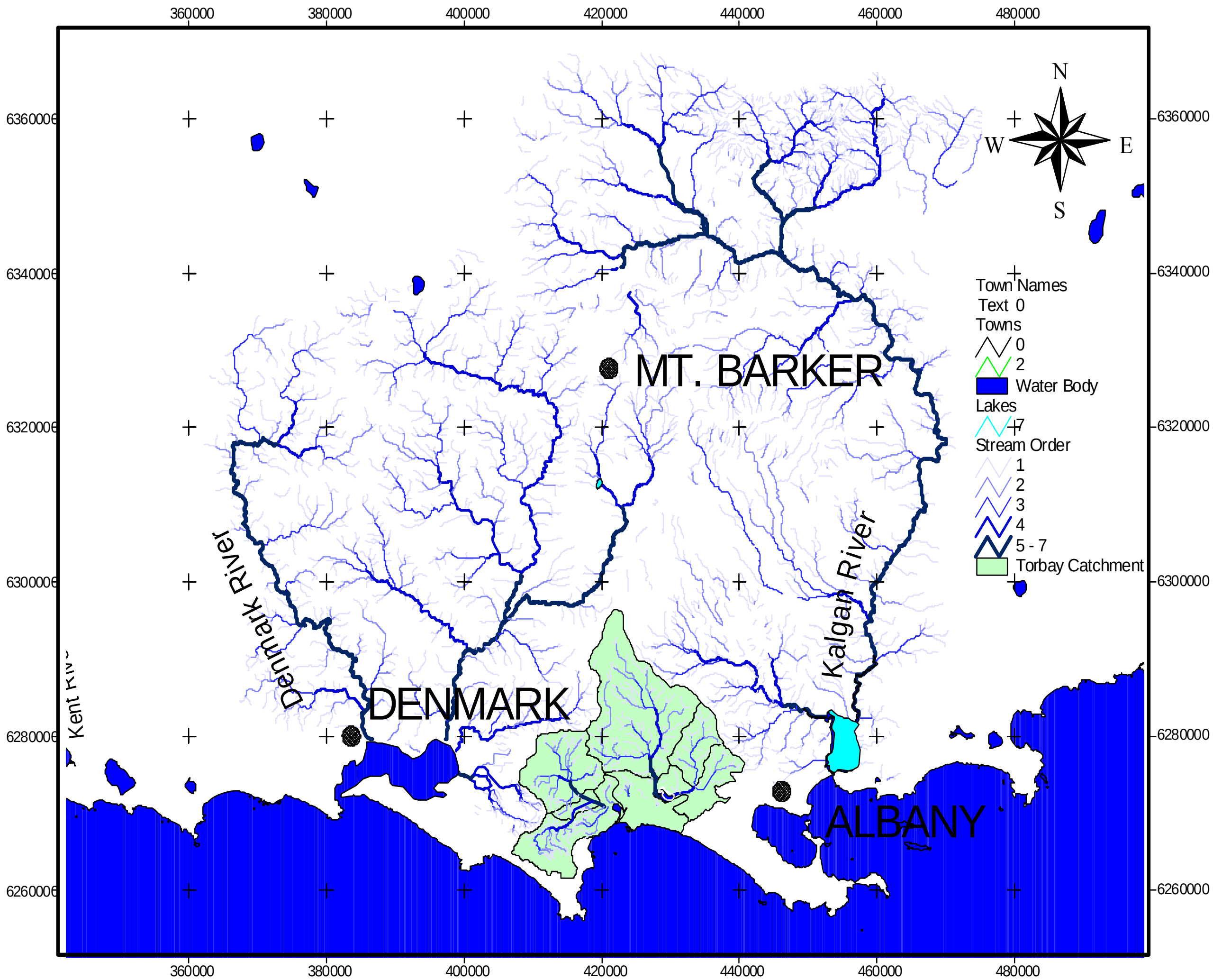


Figure 4-15 Streams or drains in Albany, Denmark and Mount Barker area

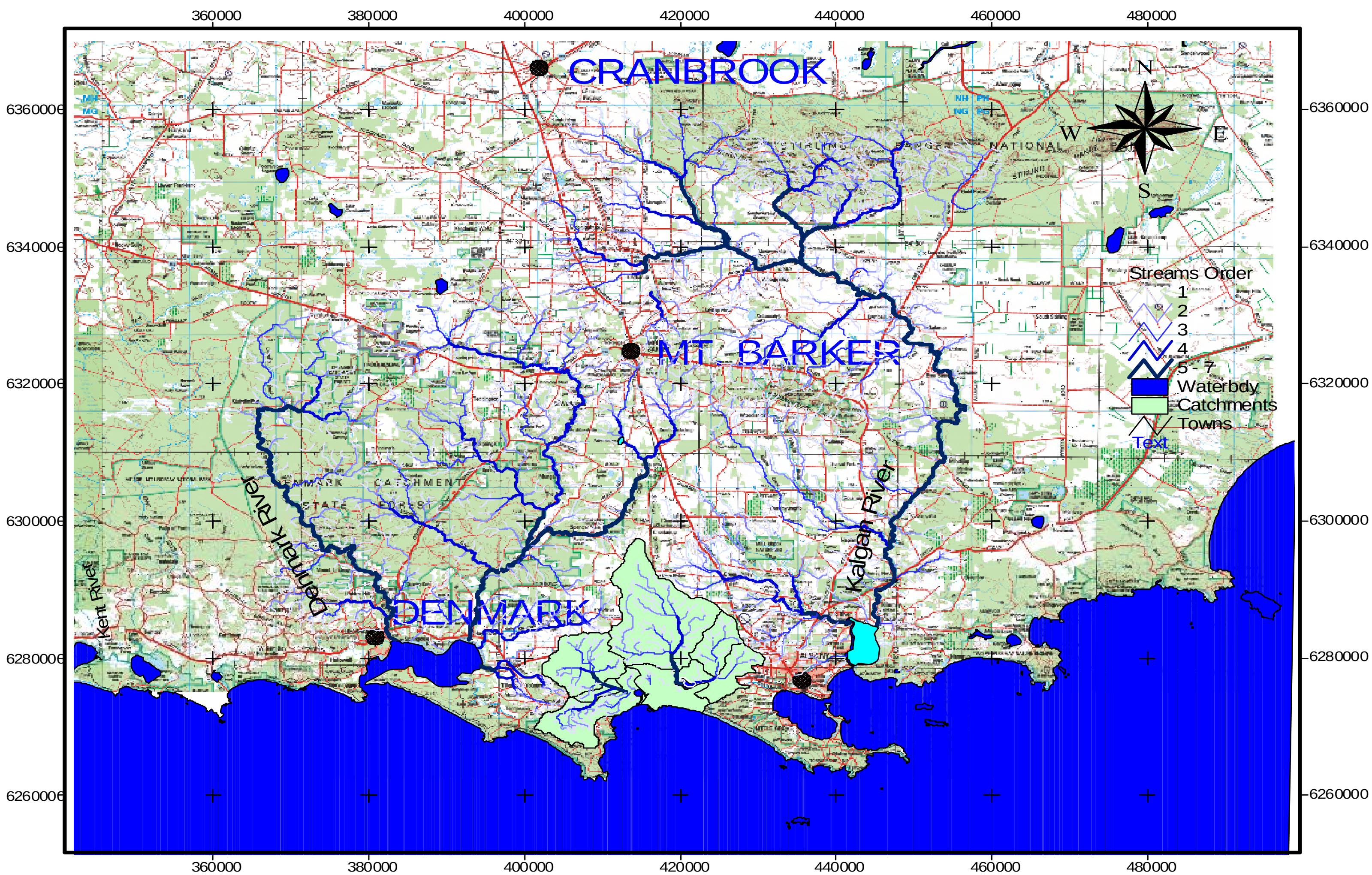


Figure 4-16 Streams or drains in Albany, Denmark and Mount Barker area overlayed on a topographic base map of Scale 1:250,000

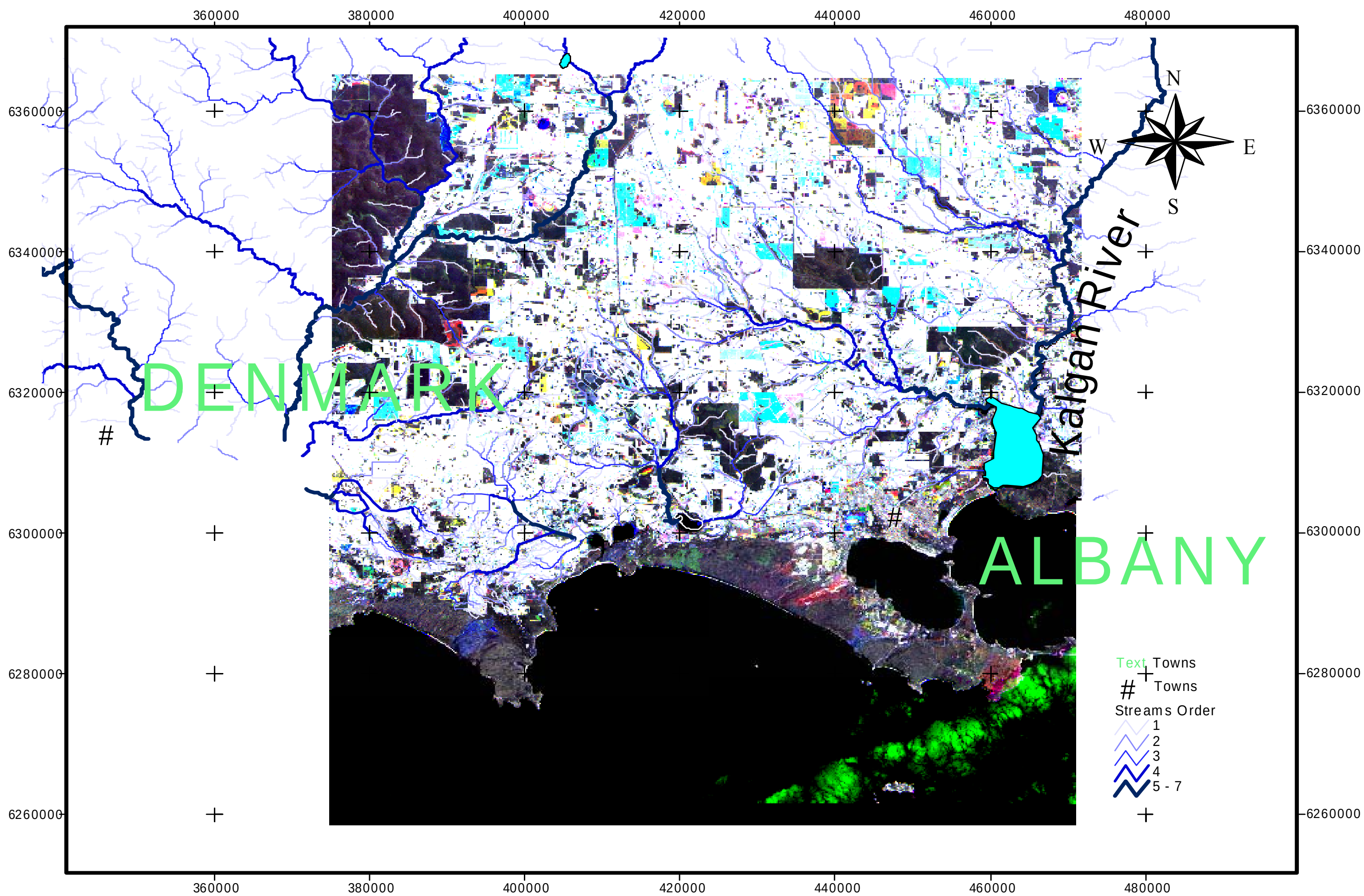


Figure 4-17 Streams or drains in Albany, Denmark and Mount Barker area overlayed on four aerial photos

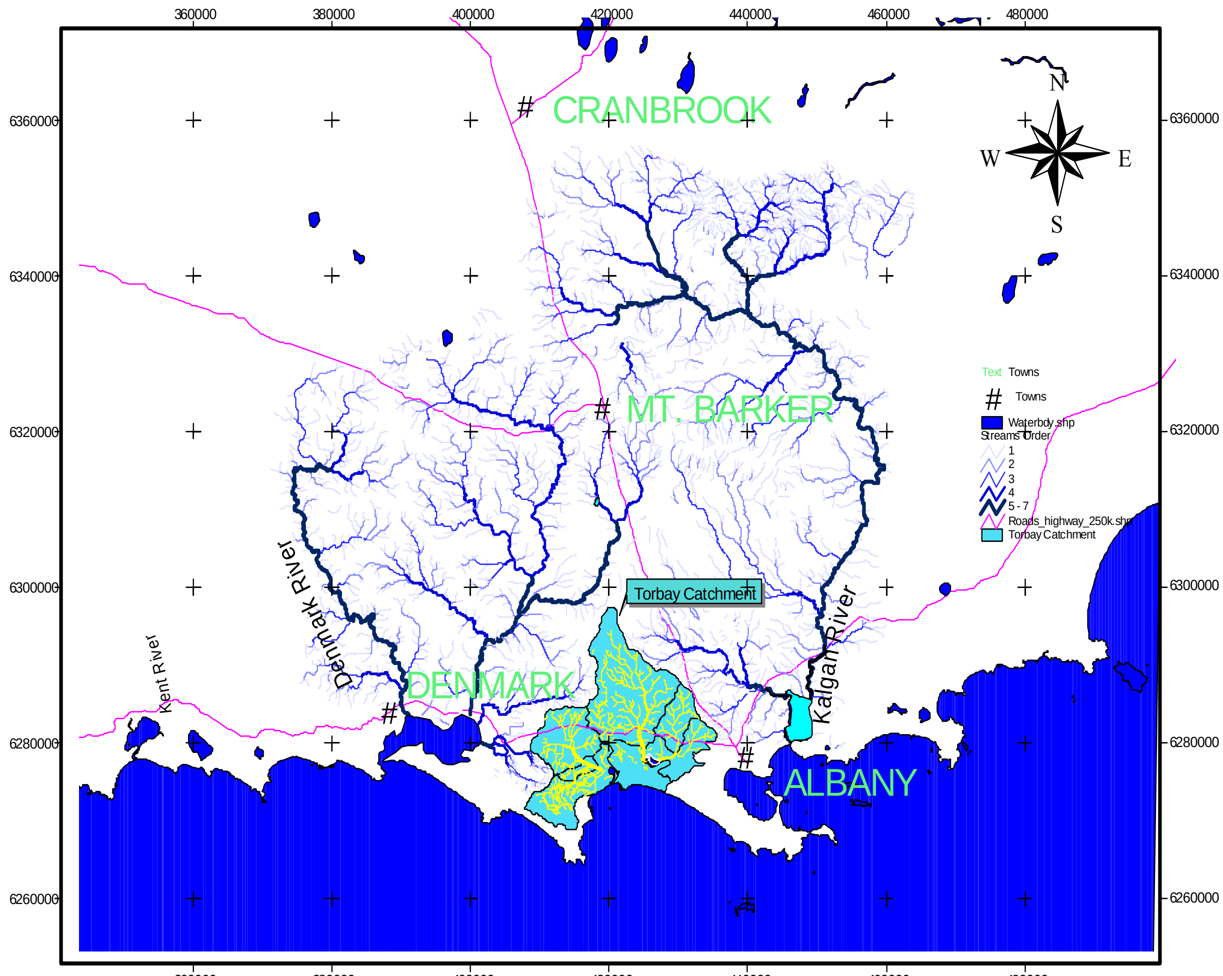


Figure 4-18 Streams or drains in Torbay Catchment

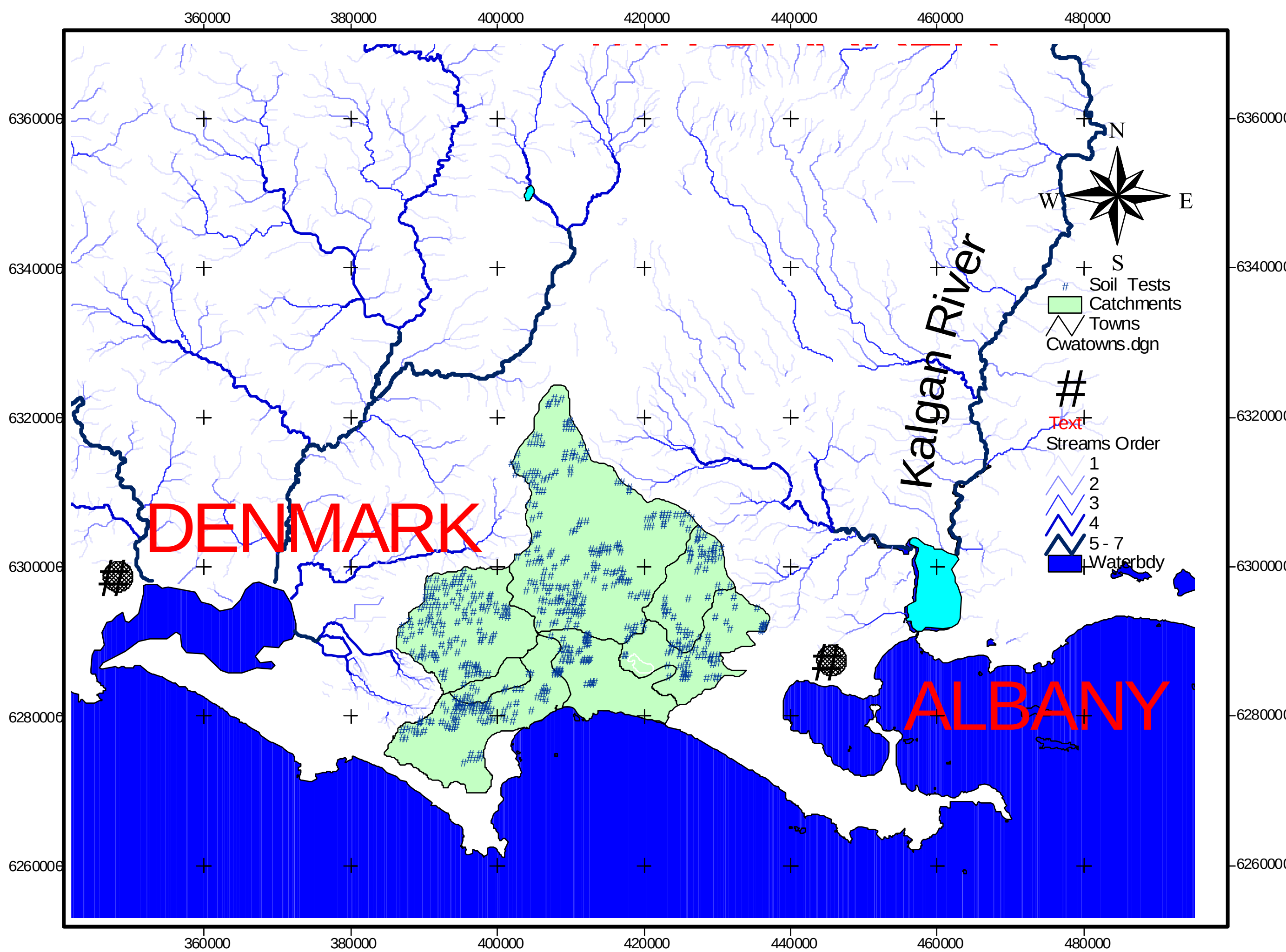


Figure 4-19 Location of soil samples in Torbay catchment

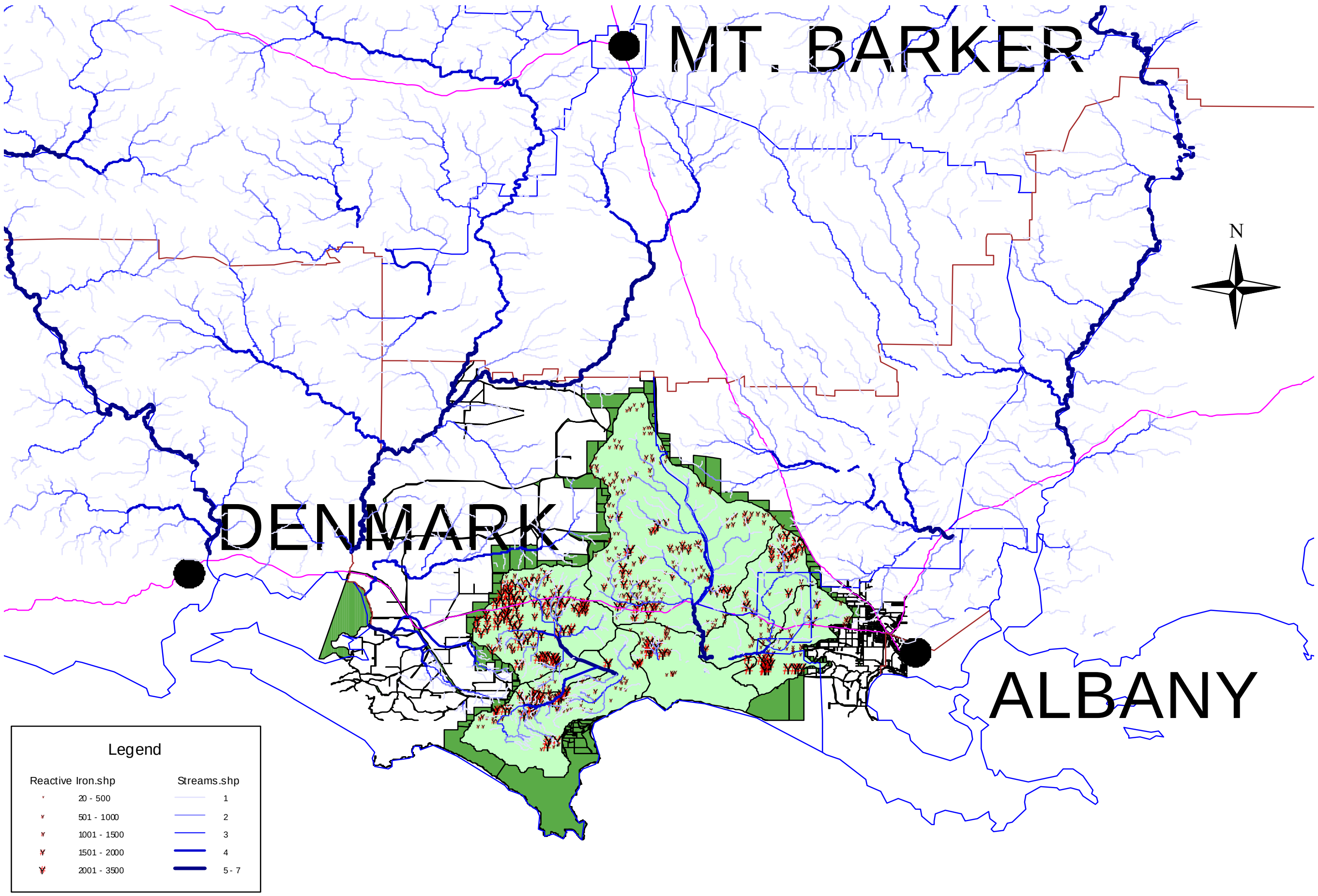


Figure 4-20 Reactive Iron in soil samples in Torbay catchment

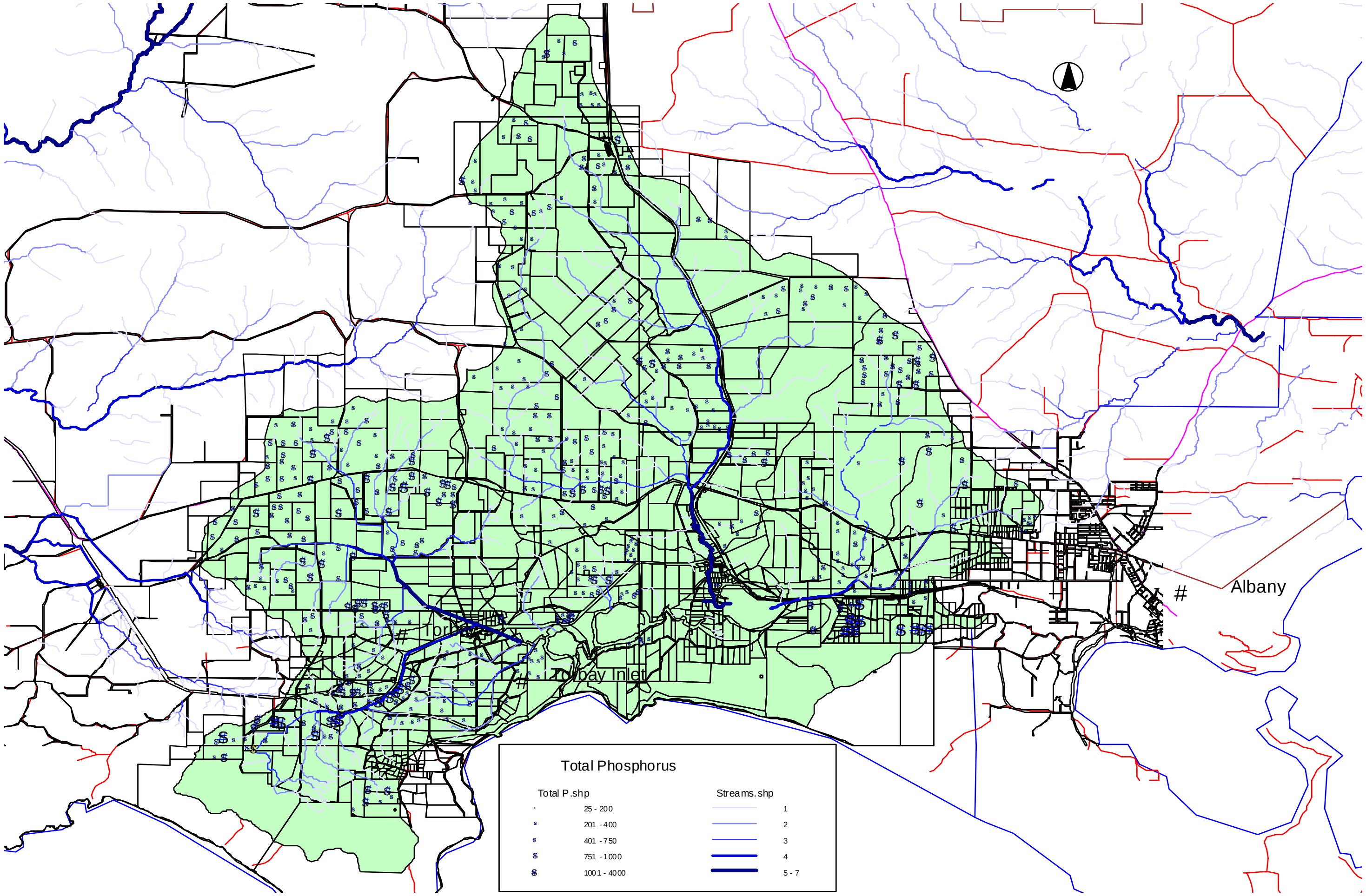


Figure 4-21 Total P in soil samples in Torbay catchment

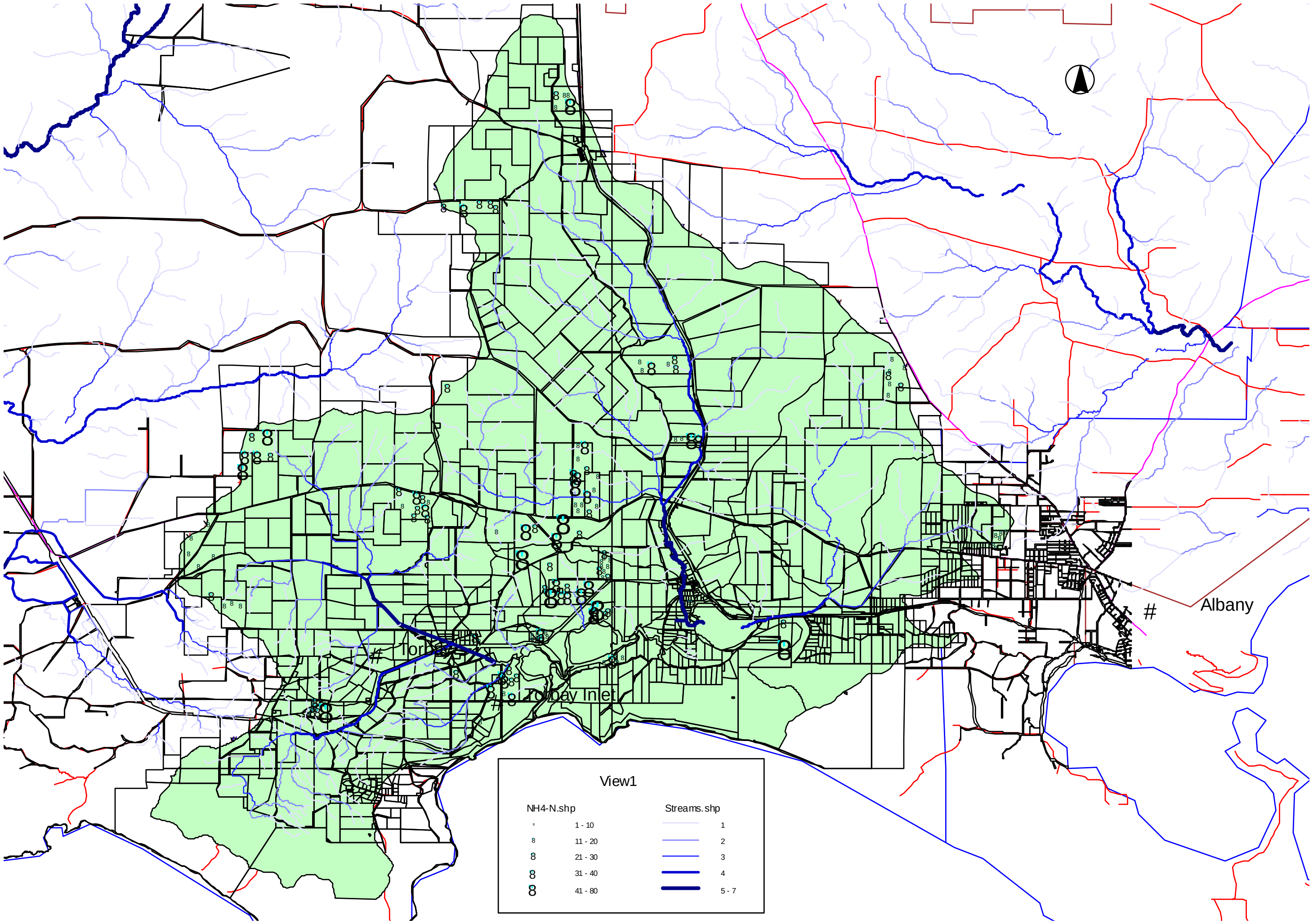


Figure 4-22 NH_4 in soil samples in Torbay catchment

5 IMPACTS OF CLIMATE CHANGE ON GROUNDWATER RECHARGE, SURFACE RUNOFF AND LAND DEGRADATION IN WESTERN AUSTRALIA

5. 1 Introduction

El Nino Southern Oscillation (ENSO) events in Australian regions result in a more pronounced cycle of prolonged droughts and heavy rains. Droughts and floods are normal and recurrent features of climate of Western Australia. Farmers in WA in the recent past experienced severe drought in 1987 and 2002 that resulted in low stream discharges and low groundwater levels. Floods in 2000 resulted in rapid increase in discharges in rivers and streams, land erosion and rapid rise in groundwater table in some areas.

Wind erosion causes land degradation during droughts when sandy and duplex soils have low vegetation cover. During heavy rainfalls water erosion and soil sealing and crusting are the major soil degradation processes. Stream salinisation is also a major problem in south-west WA. Less than 50% of the divertible surface water resources remain fresh (Western Australian Water Resources Council, 1986). One of the reasons for stream salinisation is overflow of hyper-saline water from a lake in an event of a major flood. During the 1955 flood, Lake Dumbleyung overflowed and the water in the Blackwood River became saltier (Siddiqi and Brockman, 2002). Prior to the 1955 flood there were mussels in the Blackwood, livestock were watered on the river, water was used for irrigating orchards and build up of algae did not occur. The 1955 flood permanently decreased the water level in Lake Dumbleyung, local residents recall erosion on the western side of the lake.

CSIRO (2001) has projected changes in Australian annual rainfall in 2030 and 2070 for Western Australia (Figure 5-1). There is a likelihood that a lower annual average rainfall in the south-west of Western Australia will occur and this decrease in annual rainfall will be -20 to +5% of average rainfall by 2030 and -60 to +10% of average rainfall by 2070. Northern and eastern parts of Western Australia will experience decrease in annual rainfall of -20 to +10% by 2030 and -60 to +40% by 2070. The central eastern desert area of Western Australia will have a decrease in annual rainfall of -12 to +12% by 2030 and -36 to +36% by 2070.

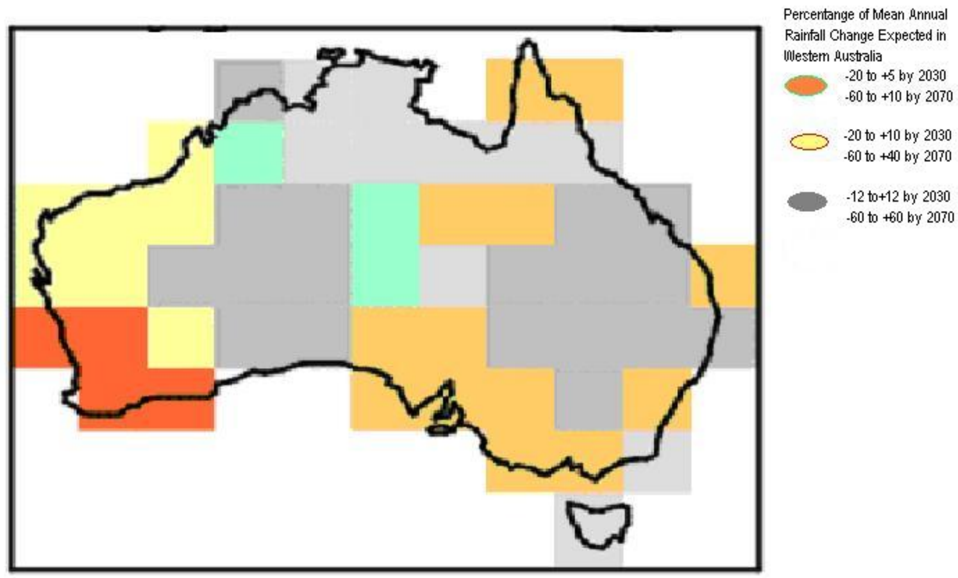


Figure 5-1 Spatial distribution of projected changes in Australian annual rainfall in 2030 and 2070 (CSIRO, 2001)

Northern Australia tends to have more pronounced wet and dry seasons and increases in extreme daily rainfall. In most of Australia the temperature will rise 0.4 to 2.0°C by 2030 and 1 to 6°C by 2070 (Climate Change 2007: Synthesis Report).

The IPCC (2007b) has also found that changing temperature and rainfall patterns are likely to result in more severe extreme events, such as droughts, floods and tropical cyclones. Land affected by extreme drought is expected to increase significantly by the end of the century (IPCC 2007b). There will be more heatwaves and fewer frosts. Tropical storms and cyclones are expected to become less frequent but the average intensity of tropical cyclones is projected to increase. There will be more severe wind speeds in cyclones, associated with storm surges being progressively amplified by rising sea levels.

Severe weather events such as storms and bushfires will increase. Extreme events such as flooding and droughts are projected to increase in frequency and severity as the global climate changes (ABARE, 2007).

Sea level has risen at an average rate of 1.8 mm per year from 1961 to 2003 and 3.1 mm per year from 1993 to 2003 (Climate Change 2007: Synthesis Report). The high rate of sea level rise is attributed to thermal expansion of the oceans.

5. 2 **Analysis of highest daily rainfalls of Western Australia using GIS**

Heavy rainfall in an area cause localised flash flooding in a short period of time. Rainfall duration, intensity and antecedent soil moisture conditions influence the flooding and inundation of low-lying areas and water levels in streams and rivers. High intensity rainfall cause sheet, rill and gully erosion and result in heavy sediment loads in streams, rivers and dams. In order to assess flooding risk in Western Australia historical maximum daily rainfall data were collected from BoM website and a map using ArcView GIS was prepared (Figure 5-3). The highest daily rainfall of different stations, day of occurrence, time period of rainfall record, eastings and northings of each station were saved in a dBase file (Appendix 5-1). In ArcView GIS this table was opened using View button and Add Event Theme command. The base map of Western Australia was prepared using Zone 50, GDA94. The eastings and northings of rainfall stations of Zone 51 were converted to Zone 50, GDA94.

Text position on a station point can be assigned by selecting properties from Theme button and in opened window select Text Labels Button, choose a Label Field from drop down menu and press on text position button and click on Scale Label before pressing OK button. Now activate the Label Theme, select Auto-label from Theme menu and tick on Use Theme's Text Label Placement Property and Scale Label buttons and press OK button. When you check on Scale Label button if the map is zoomed in or zoomed out the size of the labels will be adjusted accordingly. You need to repeat the process for each label on a label point.

The highest daily rainfall of 505 mm occurred in Kuri Bay on 17 January 1982 in the north of Western Australia during a short period of record from 1961 to 2008. The second highest rainfall of 477 mm was received at Broome Airport on 30 January 1997 between 1939 and 2008. Highest daily rainfalls of stations in Perth region with name of stations, rainfall amounts and period of rainfall records are presented in Figure 5-4. Perth Medina Research Station received the highest daily rainfall of 230 mm on 9 February 1992 for a record of the station from 1983 to 2008.

Maximum daily rainfall isohyets or contours for in Western Australia were created using methodology described in section 2.3. Inverse Distance Weighted (IDW) method with Nearest Neighbours, 0.5 degree of freedom and 50 mm contours were selected for interpolation of maximum daily rainfall data (Figure 5-5). The highest daily rainfall isohyets were labelled by selecting Auto-label from Theme command and select contour in the Label field. The highest daily rainfall isohyets of 500 mm in the north-east of Western Australia drop to 300 mm in the north of WA and to 200 mm in the middle and south-west of WA

(Figure 5-5). The historical daily rainfall of these regions will be analysed to assess the occurrence of climate change in the past and future climate change trends will be computed.

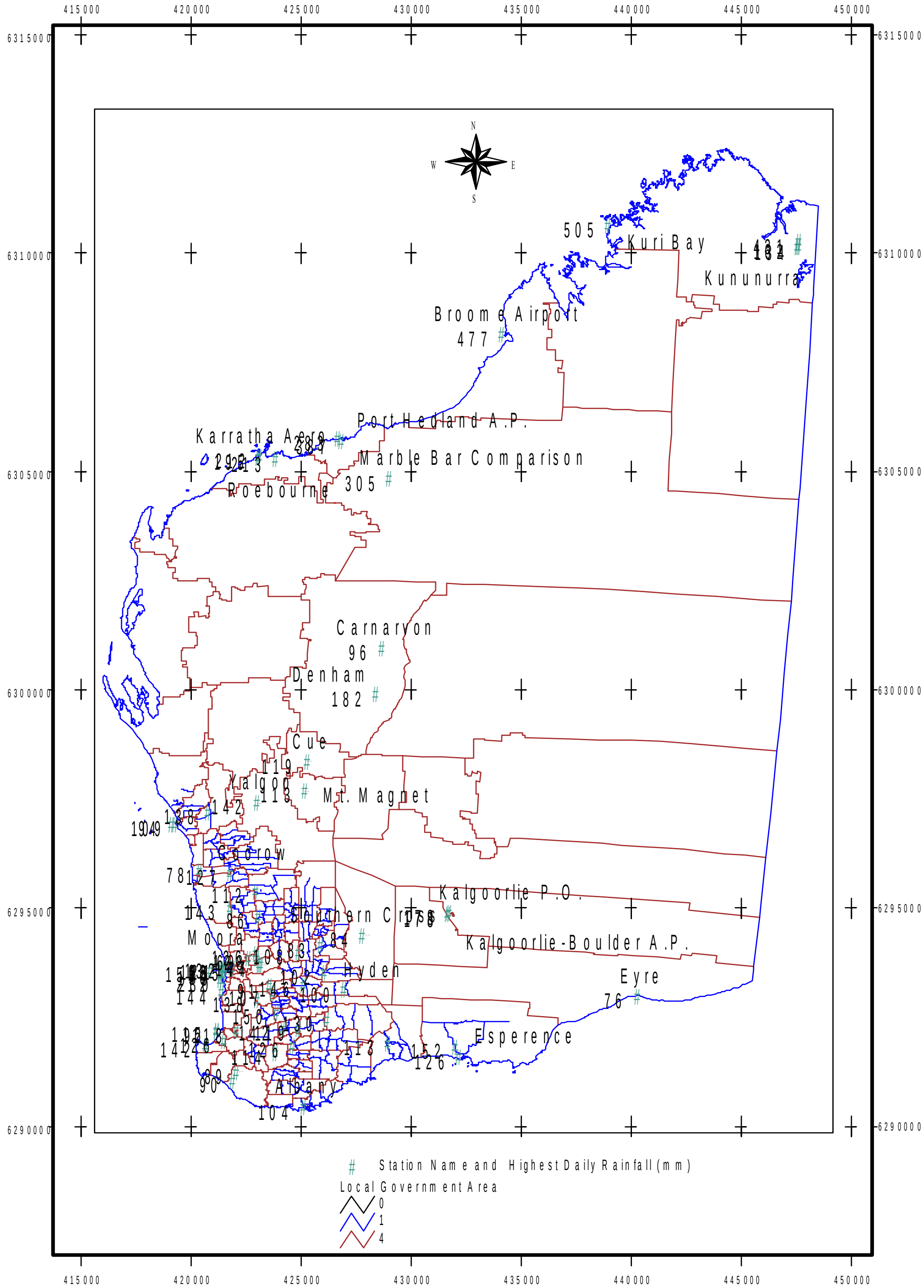


Figure 5-2 Highest daily rainfall of stations in Western Australia

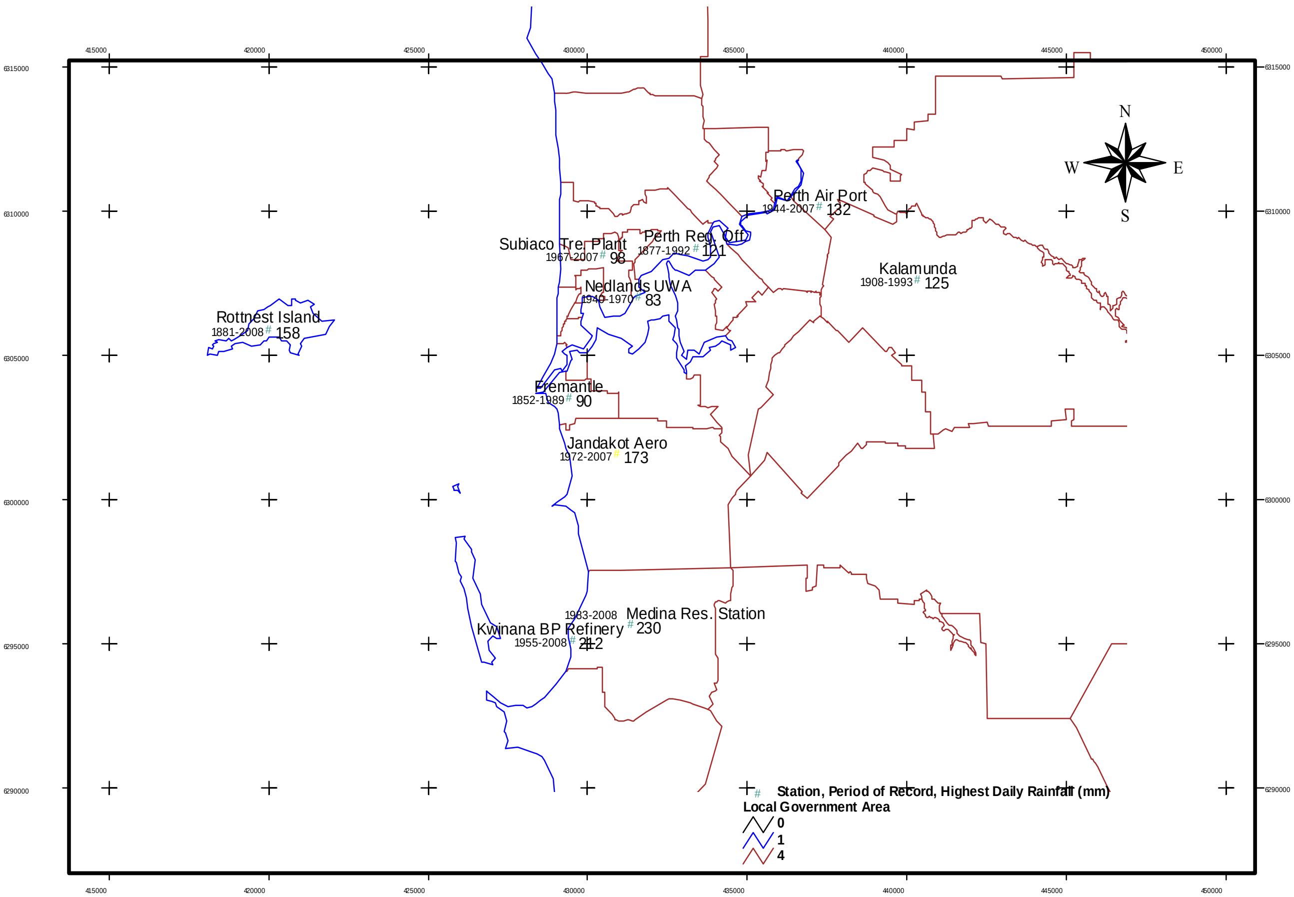


Figure 5-3 Highest daily rainfall of stations in Perth region with period of rainfall record

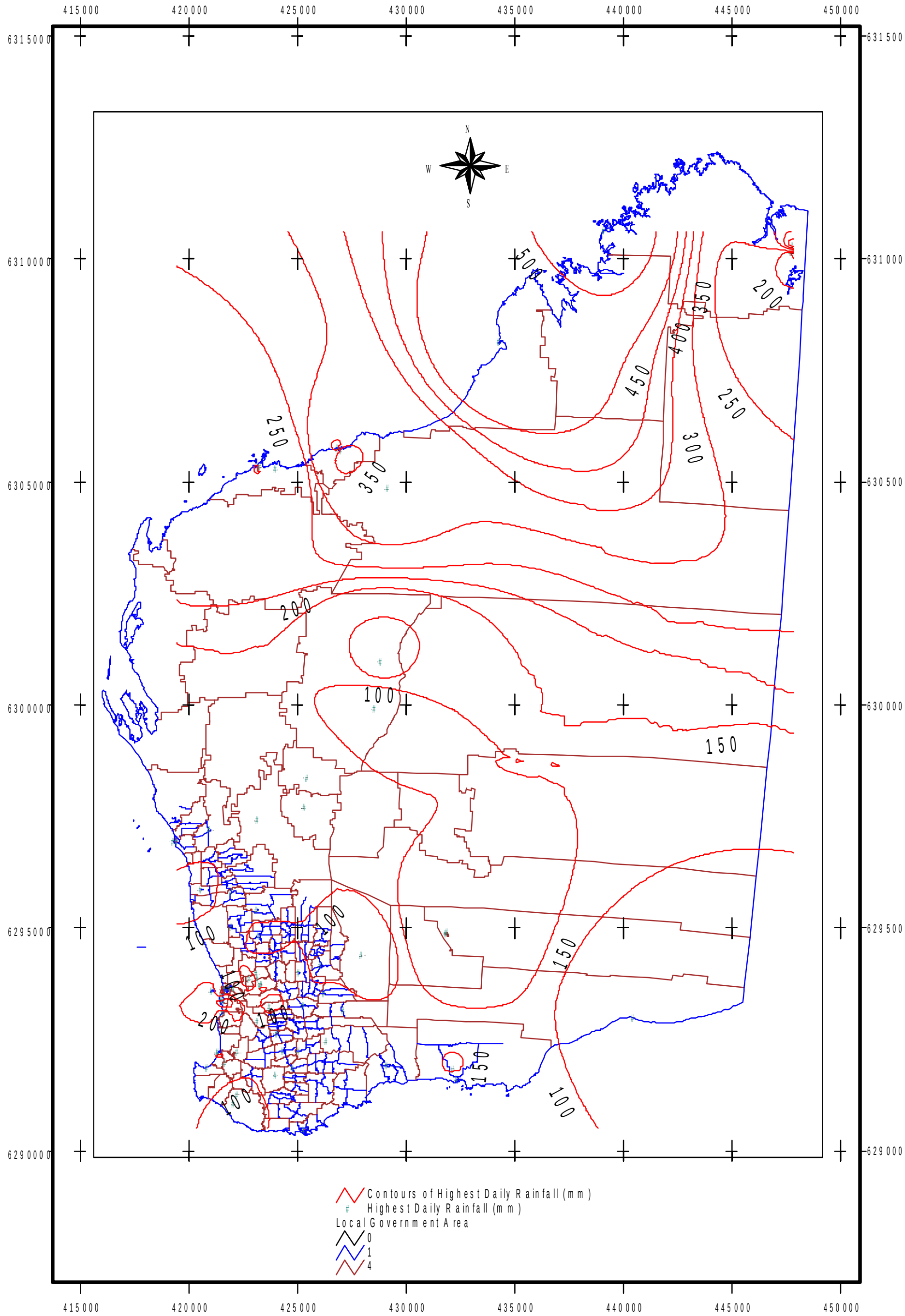


Figure 5-4 Maximum daily rainfall isohyets in Western Australia

5. 3 **Impacts of Climate Change on Surface Runoff-A Case Study of Cleo Pit**

5.3.1 Background

The Cleo Pit of Sunrise Dam Gold Mine (SDGM) is located approximately 300 km north east of Kalgoorlie. The objectives of this study are to test the hypothesis that the average intensity of tropical cyclones has increased and to determine surface runoff flow rates associated with specified rainfall events of specific annual recurrence interval. To calculate surface water runoff and peak flows at SDGM minesite using the Rational Method and other modelling approaches. To estimate the volume of surface water runoff from specified rainfall events likely to attenuate on the floor of the Cleo pit for a specified rainfall event URS (2007).

5.3.2 Cyclonic Events

Extreme rainfall events are influenced by cyclonic activity and are more likely in the summer months. Cyclones that impact coastal and adjoining areas typically form over warm ocean waters to the north of the state and move to inland areas bring with them heavy rainfall. Some of the cyclone tracks from 1979 to 2004 that might have caused episodic rainfall events at SDGM minesite are presented in Figure 5-5.

5.3.3 Daily Rainfall Data Analyses

The long-term daily rainfall data was obtained for SDGM minesite from Queensland's Department of Natural Resources from 1889 to 2007. The daily rainfall data were obtained from SILO data drill that use grids of data interpolated from point observations by the Bureau of Meteorology. The maximum daily rainfall of 92.6 mm was recorded on 24 January, 2000 in Laverton between 1889 and 2007. There were 8 days which received more than 70 mm rainfall at SDGM minesite and 28 days received rainfall in excess of 50 mm. A daily rainfall of 50 mm or more means disruptions in mining activities and an episodic event of 1.2 years out of 5 years. The daily rainfall data were totalled over 1-week duration from 1889 to 2007. The maximum weekly rainfall of 135.3 mm was received in February, 2007. There were 38 weeks which received 70 mm or more of rainfall and 66 weeks received 50 mm or more rainfall between 1889 and 2007 (Figure 5-6). These episodic rainfall events show that this area receives rainfall in cyclonic activities.

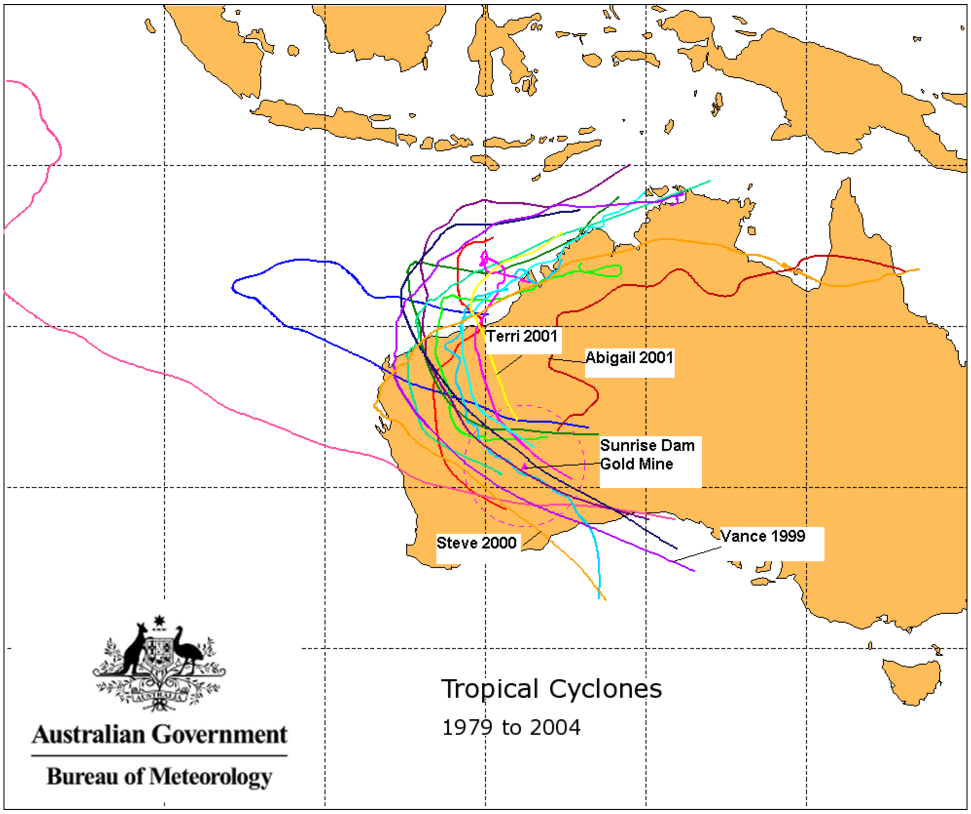


Figure 5-5 Tracks of Tropical Cyclones from 1979 to 2004 (BoM, 2007)

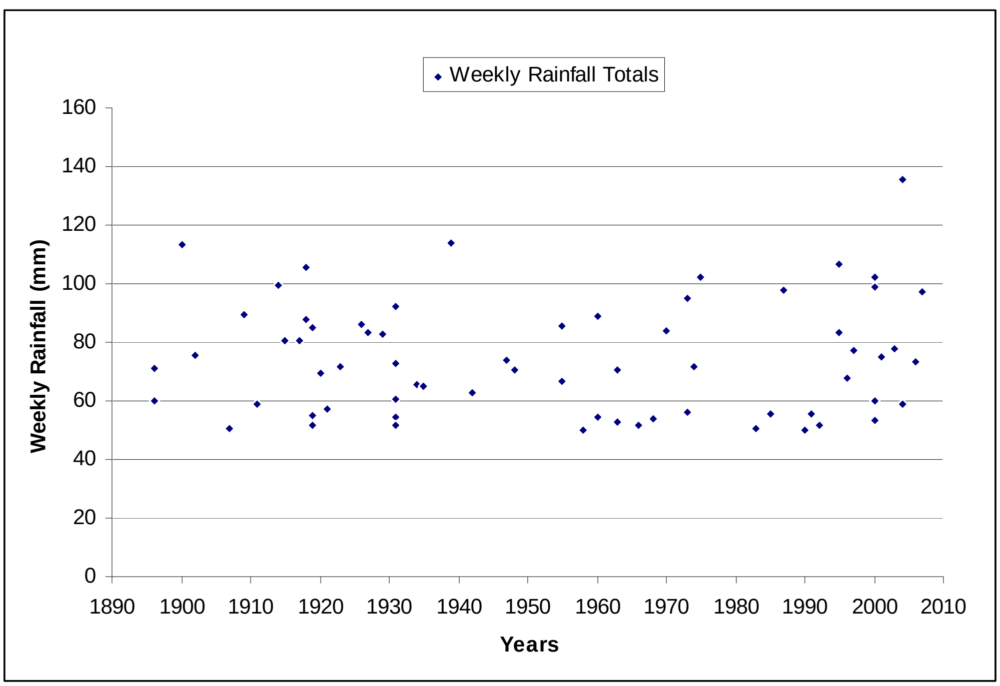


Figure 5-6 Weekly Rainfall Totals for SDGM from 1889 to 2007

5.3.4 Annual Rainfall Trends

Annual rainfall for Laverton minesite between 1889 and 2007 indicate great variability during different years. On an average Laverton minesite received annual rainfall of 223 mm with a minimum 40 mm and a maximum 526 mm. Annual rainfall from 1889 to 2007 has been plotted in Figure 5-7. During 1995, 2000, 2001 and 2004 annual rainfall was more than 400 mm at SDGM minesite. The five year moving average trend line shows an upward trend in the recent past (Figure 5-7).

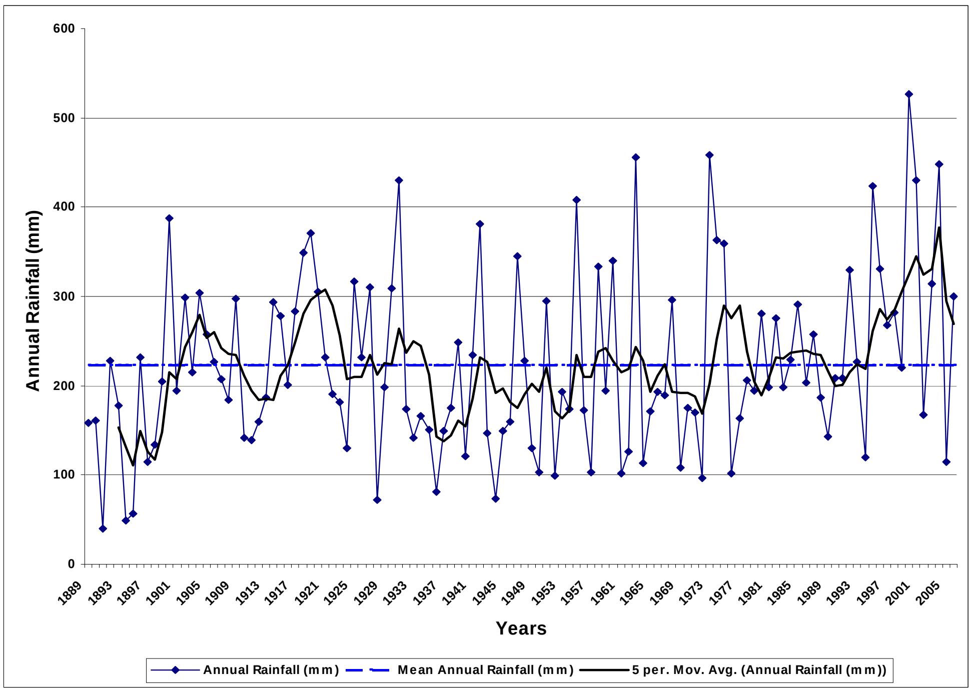


Figure 5-7 Annual rainfall trend for Laverton minesite

5.3.5 Winter Season Rainfall Trends

Winter rainfall for Laverton minesite between 1889 and 2007 had a range from 13 mm to 221 mm. On an average Laverton minesite receives 92 mm from May to October. Winter season rainfall from 1889 to 2007 has been plotted in Figure 5-8. In the recent past, winter season rainfall in 1998, 2001 and 2004 was more than the mean winter rainfall of 92 mm which might have recharged the ground water or generated surface runoff. The five year moving average trend line shows a downward trend in the winter rainfall received by Laverton minesite (Figure 5-8).

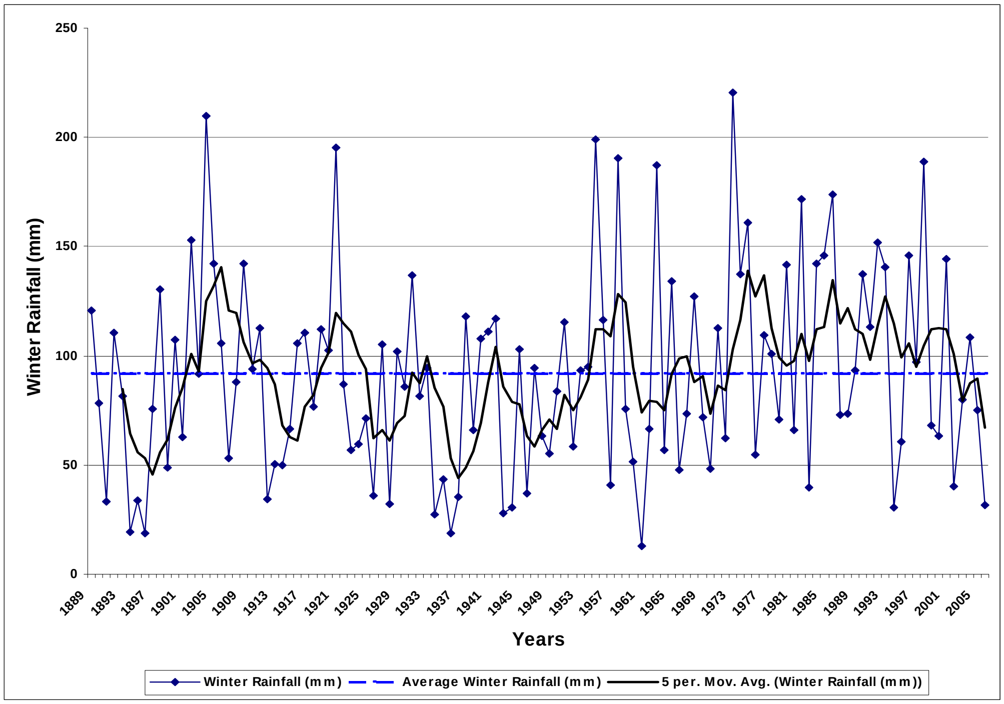


Figure 5-8 Winter season rainfall trend for Laverton minesite

5.3.6 Summer Season Rainfall Trends

The summer season rainfall has been calculated by adding rainfall during November and December of first year and rainfall from January to April in the succeeding year. Summer season rainfall from 1889 to 2007 has been plotted in Figure 5-9. Laverton minesite receives an average summer rainfall of 133 mm. The five year moving average trend line shows an upward trend in summer rainfall for Laverton minesite over the past 118 years (Figure 5-9). The summer season rainfall varies from 6 mm to 469 mm. The highest summer season rainfall was received in 2000, the second highest summer rainfall in 1995 and the third highest summer rainfall in 2004 in the past 118 years. Above average summer season rainfall occurred at SDGM minesite since 1999, except during 2005 that was a below average summer rainfall, which might have resulted in surface runoff generation or ground water recharge at Cleo Pit.

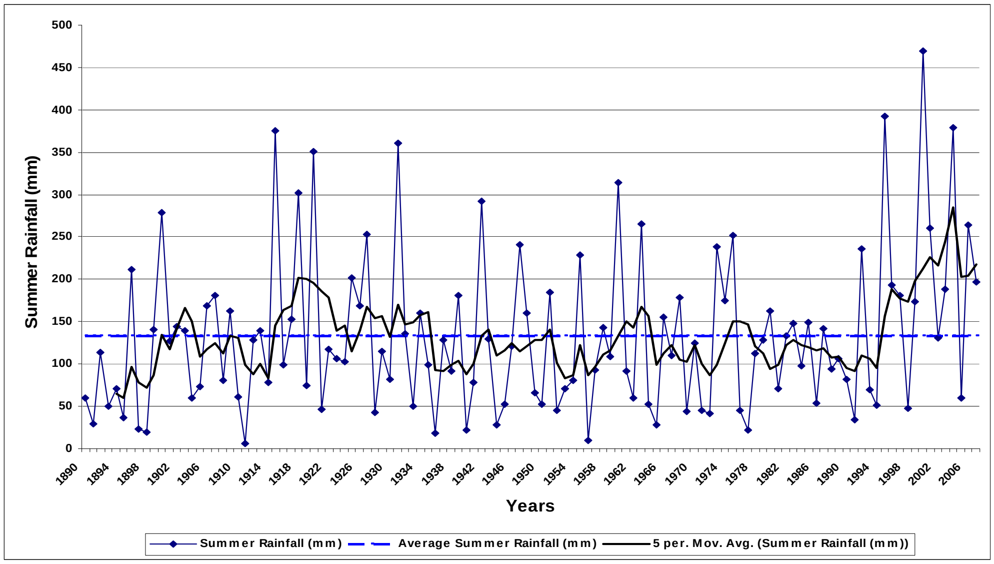


Figure 5-9 Summer season rainfall trend for Laverton minesite

5.3.7 Recording Rain Gauge Data Analysis

The rainfall intensity data was collected at SDGM minesite using a recording rain gauge from 5 October, 2001 to 1 May, 2007. The rainfall data collected at Cleo Pit using a recording rain gauge was analysed and results are presented in Table 5-3. The highest rainfall of 18.2 mm in 10 minutes duration was received on 19 September, 2006 between 5 October, 2001 and 1 May, 2007. The maximum 0.5-hr, 1-hr and 2-hr rainfall events were 34.6 mm, 42.8 and 43.0 mm, respectively during this period.

The rainfall intensities have been worked out for all rainfall events recorded at Cleo Pit and presented in Table 5-4. The maximum 10 minutes rainfall intensity recorded at Cleo pit on 19 September, 2006 was 109.2 mm hr-1 which is close to 100 years ARI of 116.6 mm hr^{-1} (Figure 5-7). The maximum 30 minutes rainfall intensity recorded at SDGM minesite on 19 September, 2006 was 69.2 mm hr^{-1} which more than 100 years ARI of 64.9 mm hr^{-1} (Appendix 5-1). The maximum 1 hour rainfall intensity recorded at SDGM minesite on 19 September, 2006 was 42.8 mm hr^{-1} which is equal to 100 years ARI of 42.3 mm hr^{-1}. The maximum 2 hours rainfall intensity recorded at SDGM minesite on 20 February, 2004 was 21.5 mm hr^{-1} which is equal to 35 years ARI of 21.9 mm hr^{-1}. These analyses show that during a short period of time from 5 October, 2001 to 1 May, 2007 SDGM minesite has received episodic rainfall events at 100 years ARI's for 10 minutes, 30 minutes and 1 hour duration. Some of these short duration rainfall events will be used to calculate runoff volumes in the following section.

Table 5-1 Highest Rainfall Events Recorded at Cleo Pit from October, 2001 to May, 2007

Date	**10-min Rainfall (mm)**	**Date**	**0.5-hr Rainfall (mm)**	**Date**	**1-hr Rainfall (mm)**	**Date**	**2-hr Rainfall (mm)**
19-Sep-06	18.2	19-Sep-06	34.6	19-Sep-06	42.8	19-Sep-06	43.0
19-Sep-06	15.2	20-Feb-04	23.8	20-Feb-04	32.4	16-Oct-01	37.0
16-Oct-01	14.0	16-Oct-01	23.0	16-Oct-01	31.0	20-Feb-04	34.4
24-Nov-02	9.8	16-Oct-01	22.0	14-Feb-04	24.4	14-Feb-04	32.2
24-Nov-02	9.8	20-Feb-04	21.6	24-Nov-02	22.2	3-Mar-04	28.6
20-Feb-04	8.8	24-Nov-02	21.2	3-Mar-04	16.2	24-Nov-02	22.2
14-Feb-04	7.6	19-Sep-06	19.2	14-Feb-04	14.2	14-Feb-04	18.8
20-Feb-04	7.6	14-Feb-04	16.8	19-Dec-06	12.4	19-Jan-02	18.0
20-Feb-04	7.4	03-Mar-04	12.0	3-Mar-04	12.4	14-Feb-04	15.8
16-Feb-04	6.6	03-Mar-04	11.8	16-Feb-04	12.2	12-Dec-02	11.6
16-Oct-01	6.0	16-Feb-04	11.4	19-Jan-02	11.0		
19-Dec-06	6.0	20-Feb-04	10.6	14-Feb-04	10.0		
19-Jan-02	5.4	16-Oct-01	8.0	3-Mar-04	8.8		
14-Feb-04	5.4	13-Feb-04	6.0	8-Feb-04	8.6		
20-Feb-04	5.4	14-Feb-04	5.6	4-Mar-04	8.0		
16-Feb-04	4.2	19-Jan-02	5.4	14-Feb-04	7.8		
14-Feb-04	4.0	14-Feb-04	5.0	14-Feb-04	7.4		
13-Feb-04	3.8	14-Feb-04	4.8	19-Jan-02	7.0		
03-Mar-04	3.8	14-Feb-04	4.4	13-Feb-04	6.8		
16-Oct-01	3.0	03-Mar-04	4.2	14-Feb-04	5.8		
19-Dec-06	2.8			8-Feb-04	5.4		

Table 5-2 Highest Rainfall Intensities Recorded at Cleo Pit from October, 2001 to May, 2007

Date	10-min Rainfall (mm)	Date	0.5-hr Rainfall (mm)	Date	1-hr Rainfall (mm)	Date	2-hr Rainfall (mm)
19-Sep-06	109.2	19-Sep-06	69.2	19-Sep-06	42.8	19-Sep-06	21.5
19-Sep-06	91.2	20-Feb-04	47.6	20-Feb-04	32.4	16-Oct-01	18.5
16-Oct-01	84.0	16-Oct-01	46.0	16-Oct-01	31.0	20-Feb-04	17.2
24-Nov-02	58.8	16-Oct-01	44.0	14-Feb-04	24.4	14-Feb-04	16.1
24-Nov-02	58.8	20-Feb-04	43.2	24-Nov-02	22.2	3-Mar-04	14.3
20-Feb-04	52.8	24-Nov-02	42.4	3-Mar-04	16.2	24-Nov-02	11.1
14-Feb-04	45.6	19-Sep-06	38.4	14-Feb-04	14.2	14-Feb-04	9.4
20-Feb-04	45.6	14-Feb-04	33.6	19-Dec-06	12.4	19-Jan-02	9.0
20-Feb-04	44.4	03-Mar-04	24.0	3-Mar-04	12.4	14-Feb-04	7.9
16-Feb-04	39.6	03-Mar-04	23.6	16-Feb-04	12.2	12-Dec-02	5.8
16-Oct-01	36.0	16-Feb-04	22.8	19-Jan-02	11.0		
19-Dec-06	36.0	20-Feb-04	21.2	14-Feb-04	10.0		
19-Jan-02	32.4	16-Oct-01	16.0	3-Mar-04	8.8		
14-Feb-04	32.4	13-Feb-04	12.0	8-Feb-04	8.6		
20-Feb-04	32.4	14-Feb-04	11.2	4-Mar-04	8.0		
16-Feb-04	25.2	19-Jan-02	10.8	14-Feb-04	7.8		
14-Feb-04	24.0	14-Feb-04	10.0	14-Feb-04	7.4		
13-Feb-04	22.8	14-Feb-04	9.6	19-Jan-02	7.0		
03-Mar-04	22.8	14-Feb-04	8.8	13-Feb-04	6.8		
16-Oct-01	18.0	03-Mar-04	8.4	14-Feb-04	5.8		
19-Dec-06	16.8			8-Feb-04	5.4		

5.3.8 Runoff Calculations

The Rational Method has been used to determine the peak flows for the Cleo Pit's catchment. A catchment area of 250 ha was calculated for Cleo Pit using a high resolution Google Earth image in ArcView GIS (Figure 5-10). The Rational Method is a universally accepted simplistic method to calculate the peak flood flows of selected Average Recurrence Intervals (ARI) from an average rainfall intensity of the same ARI. The Rational Method incorporates the intensity of the rainfall, the area of the catchment and a coefficient of runoff.

Figure 5-10 Cleo Pit Catchment and Pit Areas

The coefficient of runoff for a catchment depends on the following inter-related factors:

- Soil type and permeability;
- Land vegetation type, density and slope; and
- Intensity of rainfall.

The Rational Formula used for the estimation of the peak discharge is given in Equation 5-1.

$$Q = 0.00278\ C\ I_{tcY}\ A \qquad (5\text{-}1)$$

Where

Q = Peak discharge (in $m^3\ s^{-1}$);

C = A dimensionless run-off coefficient;

I = Mean rainfall intensity (mm hr^{-1}) of a storm of the design ARI and duration equal to the time of concentration, t_c;

A = Catchment area (ha);

The relevant equation to calculate t_c is given below (Pilgrim, 2001).

$$t_c = 0.76\ A^{0.38}$$

5.3.9 Design Rainfall Intensities

The peak rainfall intensity data for 1-hour, 12- hour and 72-hour durations for 2 and 50-year ARIs, geographical factors for 2- and 50-year ARIs, and average regional skewness were obtained from AR&R (1987). The rainfall intensities (mm $hour^{-1}$) for different durations and ARIs between 1 and 100 years were then computed for Cleo Pit and used to calculate peak discharges (Figure 5-11).

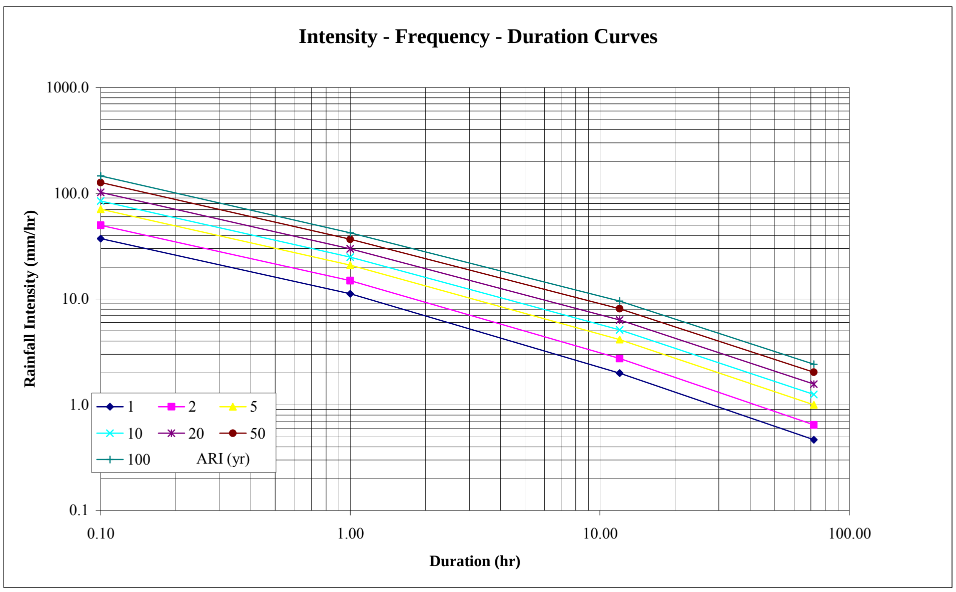


Figure 5-11 Design Rainfall Intensity Diagram for Cleo Pit

5.3.10 Runoff Coefficient 'C'

In order to estimate Rational Runoff coefficient 'C' for different soil type with multiple land uses and slopes all the catchment of Cleo Pit was subdivided into sub-catchments. An average coefficients 'C' for composite areas was calculated on an area weighted basis using:

$$C = \frac{\sum Ci \times Ai}{\sum Ai}$$

An average runoff coefficient of 0.7 for composite areas of Cleo Pit was used in the runoff volume calculations presented in Table 5-6.

Table 5-3 Rainfall Intensities (mm hr^{-1}) for Cleo Pit

Duration	**Average Recurrence Interval in Years**						
(Hours)	**1**	**2**	**5**	**10**	**20**	**50**	**100**
0.5	16.94	22.62	31.90	37.93	45.64	56.33	64.90
1	11.18	14.90	20.94	24.84	29.84	36.75	42.28
6	3.23	4.39	6.51	7.94	9.77	12.37	14.49
12	1.99	2.73	4.13	5.10	6.33	8.10	9.55
24	1.17	1.61	2.46	3.05	3.80	4.89	5.78
48	0.67	0.92	1.42	1.77	2.22	2.87	3.40
72	0.47	0.64	1.00	1.25	1.57	2.03	2.42

- It is assumed in this study that the current Cleo Pit flood defences are operating sufficiently, i.e. no drainage channels are blocked causing water from the wider catchment to inundate the pit. Therefore, only the Cleo Pit catchment area will be considered as the potential generator of surface runoff.
- The Cleo Pit flood defences are designed to a 1:100 year standard, therefore the design ARI of design rainfall events will not exceed a 1:100 ARI.

It has been assumed that the Cleo Pit has the characteristics typical of rocky hills. Therefore, the time of concentration (t_c) was calculated as fifty minutes. The predicted runoff rate and runoff volumes are given for Cleo Pit for different ARI's in Tables 5-4 and Table 5-5, respectively. The catchment peak flows are calculated for 0.5-, 1-, 6-, 12-, 24-, 48- and 72-hour rainfall events, for 1-,2-, 5-, 10-, 20-, 50- and 100-year Average Recurrence Intervals (ARI's). As an example, the Cleo minesite catchment of 250 ha will have a flow rate of 2.3 m^3 s^{-1} in 6 hours of duration at 10 years ARI (Table 5-4) with a runoff volume of 50,062 m^3 (Table 5-5). Similarly, the Cleo Pit will experience a runoff rate of 1.4 m^3 s^{-1} in 72 hours duration at 100 years ARI (Table 5-5) and a volume of 368,831 m^3 will be generated (Table 5-5).

5.3.11 Predicted Runoff Rates and Volumes Using Recorded Rainfall Events

Time-Area method has been used to derive a flood hydrograph for the Cleo Pit for a 250 ha catchment for a rainfall event on 19 September, 2006 (Figure 5-13). The rainfall hyetograph has been shown in Figure 5-12. The catchment has a time of concentration of 50 minutes. It is divided into five zones by isochrones 10 minutes apart with five contributing areas each of a 50 ha area.

Flavell and Belstead (1986) used the Initial Loss-Continuous Loss (IL-CL) model to obtain design losses for catchments in Western Australia. They found that IL decreased with ARI in the region where flooding tends to increase towards the end of winter as catchments become wetter with the rarer events being associated with high antecedent wetness. In the other regions, IL increased with ARI up to 10 years, and then decreased. A minimum IL of 20 mm was obtained with an ARI of 2 years for loamy soil areas, and a maximum IL of 98 mm was derived with ARI of 10 years for sandy soil catchments. This indicates the broadness of the range of values of this parameter. For the same data, CL varied from 3 mm h^{-1} to 5 mm h^{-1}.

An Initial Loss-Continuing Loss model was applied with an initial loss of 7 mm and a continuing loss rate of 0.2 mm per 10 minutes is subtracted from rainfall depths. A 50 minutes rainfall event had a rainfall depth of 42.6 mm with an average rainfall intensity of 51.1 mm hr^{-1}. Flow rates of every 10 minutes were calculated and the runoff hydrograph is presented in Figure 5-13. There was 87,500 m^3 volume of runoff produced from a 35 mm of net rainfall on 19 September, 2006 with a flow rate of 0.292 m^3 s^{-1} at Cleo pit.

Table 5-4 Predicted Runoff Rate at Different ARI's for Cleo Pit

Duration (Hours)	**Peak Runoff Rate (m^3s^{-1}) at Average Recurrence Interval in Years**						
	1	**2**	**5**	**10**	**20**	**50**	**100**
0.5	4.12	5.50	7.76	9.23	11.10	13.70	15.79
1	2.99	3.99	5.60	6.65	7.98	9.83	11.31
6	0.94	1.28	1.90	2.32	2.85	3.61	4.23
12	0.73	1.00	1.51	1.86	2.31	2.96	3.48
24	0.46	0.63	0.96	1.19	1.48	1.90	2.25
48	0.29	0.40	0.62	0.77	0.97	1.26	1.49
72	0.27	0.37	0.58	0.73	0.92	1.19	1.42

Table 5-5 Predicted Runoff Volume at Different ARI's Cleo Pit

Duration (Hours)	**Peak Runoff Volumes (m^3) at Average Recurrence Interval in Years**						
	1	**2**	**5**	**10**	**20**	**50**	**100**
0.5	7,400	9,900	13,970	16,610	19,980	24,660	28,420
1	107,70	14,350	20,170	23,930	28,740	35,400	40,730
6	20,370	27,680	41,050	50,060	61,600	77,990	91,360
12	31,370	43,030	65,100	80,390	99,780	127,680	150,530
24	39,340	54,140	827,20	102,560	127,780	164,435	194,360
48	50,690	69,610	107,440	133,920	167,970	217,150	257,250
72	71,120	96,850	151,320	189,150	237,570	307,180	368,830

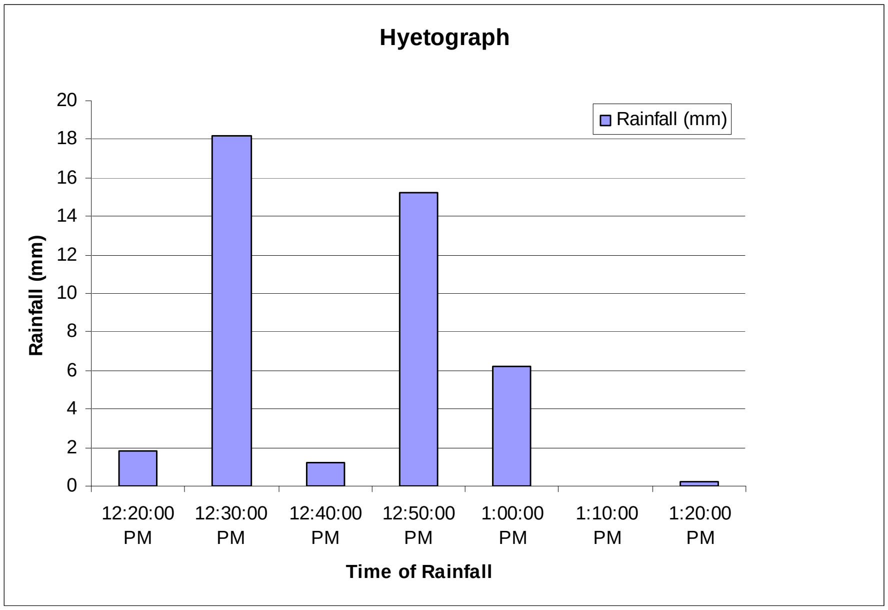


Figure 5-12 Rainfall Hyetograph Recorded at Cleo Pit on 19 September, 2006

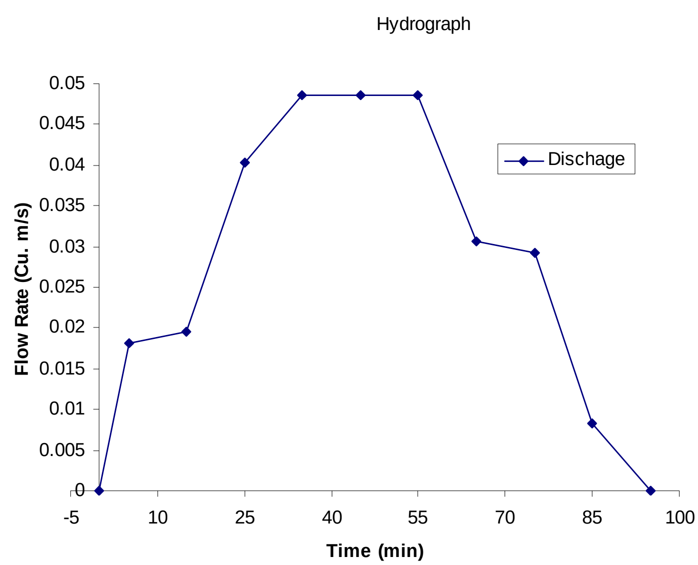


Figure 5-13 Runoff Hydrograph of Cleo Pit for 19 September, 2006

The Rational Method was also used to determine the peak flows for the Cleo Pit's catchment area of 250 ha. The average rainfall intensity of 51.1 mm hr^{-1} and a runoff coefficient 0.82 for 1-yr ARI produced the flow rate of 0.292 m^3 s^{-1} and a volume of surface water runoff of 87,016 m^3. This analysis shows that an IL-CL model can be used to calculate surface runoff at Cleo pit with rainfall intensity data.

There was a wet spell from 13 February, 2004 to 21 February, 2004 when 216 mm rainfall was recorded at Cleo Pit. The rainfall was recorded continuously for 33 hours from 13 February to 15 February, 2004 and for 5 hours on 16 February, 2004 and 6 hours from 20 to 21 February, 2004. The combined hyetograph for this period has been shown in Figure 5-14. An initial loss of 10 mm and a continuing loss rate of 1 mm per hour were subtracted from rainfall depths which resulted in a net rainfall excess of 154 mm. The flow rate of 1.07 m^3 s^{-1} was calculated for the Cleo Pit's catchment area of 250 ha which is less than the flow rate of 72 hours rainfall event of 50 years ARI (Table 5-5).

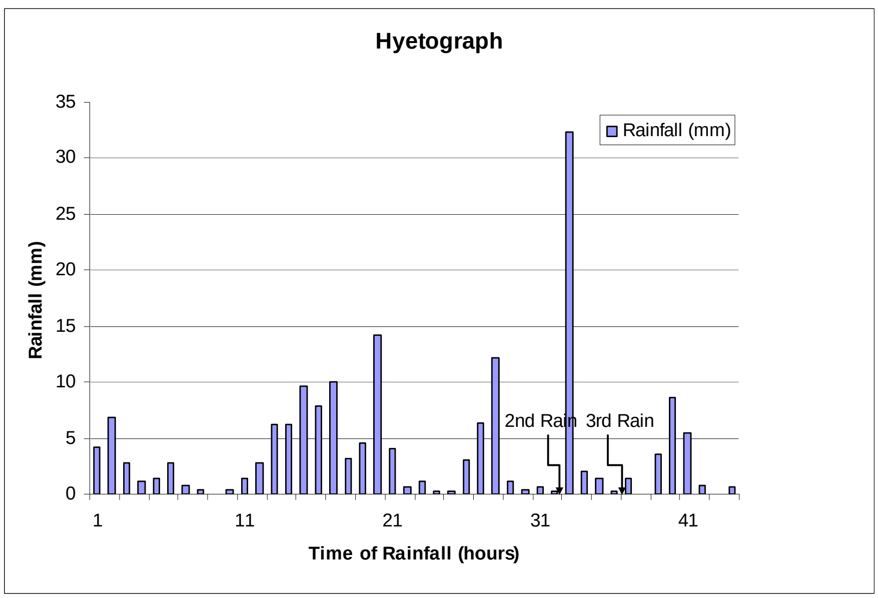


Figure 5-14 Rainfall Hyetograph Recorded from 13-21 February 2004 for Cleo Pit

The maximum 24 hours rainfall was recorded on 14 February, 2006 for the recording rain gauge record from 5 October, 2001 to 1 May, 2007. The total depth of rainfall was 128 mm and the hyetograph for this event has been presented in Figure 5-15. An initial loss of 10 mm and a continuing loss rate of 2 mm per two hours were subtracted from rainfall depths which resulted in a net rainfall excess of 97.4 mm. The flow rate of 0.68 m^3 s^{-1} was calculated for the Cleo Pit's catchment area of 250 ha which is more than the flow rate of 24 hours rainfall event of 2 years ARI but less than flow rate of 24 hours rainfall event of 5 years ARI (Table 5-4). The surface water volume of 58,752 m^3 was calculated for the rainfall event on 14 February, 2004 which is more than the surface water volume of 54,139 m^3 calculated for a 24 hours rainfall event of 2 years ARI (Table 5-5). If surface water volume of 58,752 m^3 is attenuated in the Cleo Pit floor in a one hectare area it will have a depth of 5.88 m.

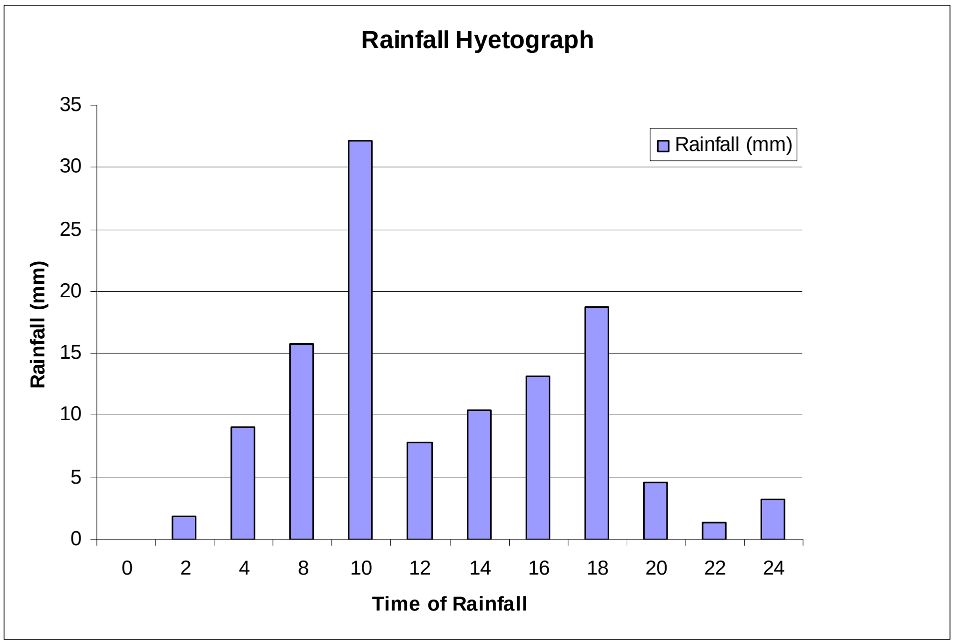


Figure 5-15 Rainfall Hyetograph Recorded on 14 February 2004 for Cleo Pit

In recent years, the attenuation of surface water runoff at the bottom of the Cleo pit at Sunrise Dam Gold Mine (SDGM) has been observed during and after certain rainfall events. This has occurred even with the 1:100 year flood defenses in situ protecting the pit from flood water generated in the local catchment. This has raised questions about the potential for the pit itself to generate significant volumes of water and the risk posed to the underground workings in the minesite.

The analyses of long-term daily rainfall data and rainfall intensity data show that the SDGM minesite is prone to episodic rainfall events which produce large volumes of surface runoff. The analyses carried out to produce estimate of the potential volumes of water and their depths to be attenuated in the Cleo Pit is based on methodology developed by Pilgrim (2001). It is recommended that for any specific use of the peak flood volumes and their depths should be estimated again for in-situ conditions existing in the Pit and its catchment at the time of analyses. The recording rain gauge installed at Cleo Pit located approximately 300 km north east of Kalgoorlie received

30-minutes and 1-hour rainfall intensity of more than 100 ARI between 5 October, 2001 and 1 May, 2007. The maximum weekly rainfall of 135.3 mm was received in February, 2007 when daily rainfall data were totaled for 1-week duration from 1889 to 2007. The annual and summer season rainfall has shown an upward trend in the recent past.

5. 4 Impacts of Climate Change on Groundwater Recharge and Surface Runoff - A Case Study of Buntine-Marchagee Natural Diversity Recovery Catchment

In this section a climate change study will be conducted for northern Wheatbelt and impacts of climate change on groundwater recharge and surface runoff will be studied.

5.4.1 Climate

The Buntine-Marchagee Natural Diversity Recovery Catchment (BMNDRC) covers 181,000 hectares in the northern Wheatbelt of Western Australia. Climate in the BMNDRC is a Mediterranean-type, with mild wet winters and warm to hot summers (URS, 2007). Rainfall extremes recorded at Coorow and Dalwallinu are provided in Table 5-7. Average annual rainfall decreases from west to east across the BMNDRC, being 379 mm at Coorow (BOM, 2006) and decreasing to 314 mm in Dalwallinu (from 1912 to 2006 and 1913 to 2006, respectively). On average, about 80% of the rainfall occurs from April to October inclusive. Extreme rainfall events are influenced by cyclonic activity and are more likely in the summer months. For example, in Dalwallinu the highest monthly rainfall of 200.5 mm was recorded in March 1999, with 140 mm falling over three days subsequent to Cyclone Elaine. A maximum daily rainfall of 112.3 mm was received in Dalwallinu on 28th March 1971.

5.4.2 Evaporation

Evaporation is measured from an open pan called a Class ‘A’ Evaporation Pan. The rate of evaporation depends on factors such as cloudiness, air temperature, air humidity and wind speed. The Bureau of Meteorology has collected evaporation data from 1975 to 2005 for Moora to the south of the BMNDRC and Three Springs to the north of the catchment.

There are no pan evaporation data available at BMNDRC and the average of pan evaporation recorded at Moora and Three Springs (Table 5-8) will be used to estimate pan evaporation within the BMNDRC. Average annual pan evaporation is six times the mean annual rainfall (Luke *et al*., 2003).

Table 5-6 Rainfall Extremes Recorded at Coorow and Dalwallinu (Record Period from 1912/1913 to 2006)

Month	Highest Daily Rainfall (mm)		Highest Monthly Rainfall (mm)		Lowest Monthly Rainfall (mm)	
	Coorow	Dalwallinu	Coorow	Dalwallinu	Coorow	Dalwallinu
January	99.2	90.6	138.0	134.6	0	0
February	58.0	79.5	96.7	103.9	0	0
March	137.9	112.3	163.8	200.5	0	0
April	126.7	111.0	144.5	126.3	0	0
May	87.4	65.6	169.8	147.1	0	0.8
June	65.5	94.7	228.7	184.6	8.2	6.3
July	46.6	46.8	198.0	144.9	10.9	17.4
August	79.5	84.8	182.8	141.0	11.4	7.9
September	64.3	49.8	97.4	68.6	1.3	1.8
October	42.7	59.4	76.5	74.2	0	0.5
November	44.8	52.3	61.8	100.1	0	0
December	51.1	40.1	61.1	66.3	0	0

Source: Bureau of Meteorology (2006), Coorow Station No. 008037, Dalwallinu Station No. 008039

Table 5-7 Monthly and Annual Average Class A Pan Evaporation Rates (mm) for Moora and Three Springs With Estimated BMNDRC Evaporation Rates

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Moora	366	333	291	173	113	73	70	91	124	193	269	360	2456
Three Springs	404	370	324	209	137	81	99	109	143	226	293	387	2781
BMNDRC	385	352	308	191	125	77	85	100	134	210	281	374	2619

5.4.3 Seasonal Rainfall Trends

Winter rainfall records from 1912 to 2005 for Coorow plotted in Figure 5-16, indicate great variability. On average Coorow receives 258 mm of rainfall from May to October. During 1917 and 1963, winter rainfall was 277 mm more than the mean winter rainfall of 258 mm. Coorow received below average winter rainfall in each of the last nineteen years except 1996. During 2004, winter rainfall was the lowest on record, 244 mm below the mean.

The five-year moving average trend line shows a downward trend in the winter rainfall received by Coorow over the last 94 years (Figure 5-16). This downward trend of winter rainfall would reflect lower recharge to groundwater and surface runoff.

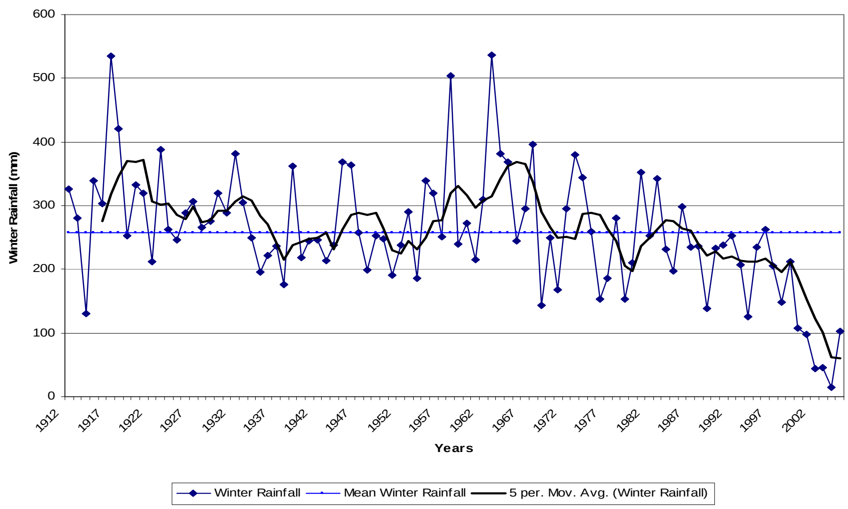


Figure 5-16 Winter rainfall trend for Coorow

The summer season rainfall has been calculated by adding rainfall during November and December of the first year and rainfall from January to April in the succeeding year. Coorow receives an average summer rainfall of 132 mm. The five–year moving average trend line shows an upward trend in summer rainfall for Coorow over the past 94 years (Figure 5-17). This increase in summer rainfall may be linked to an increase in the frequency of summer storm events.

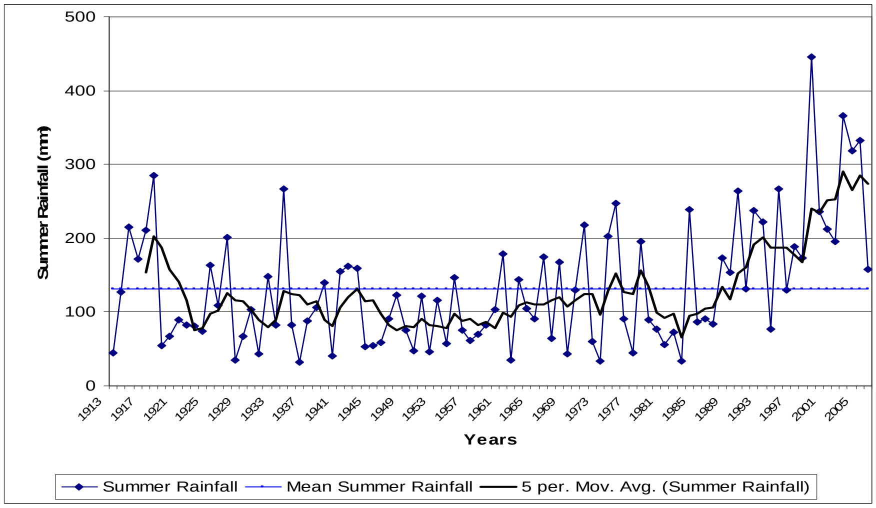


Figure 5-17 Summer rainfall trend for Coorow

5.4.4 Daily Soil Water Balance Model

A simple mathematical representation of sub-surface soil drainage and recharge is a bucket model. Bucket models are generally conceptualised as the water capacity of the root zone across the catchment. The bucket fills with infiltration and empties through evapotranspiration. Actual evaporation and soil moisture are calculated on the basis of a simple daily soil water balance. Potential evapotranspiration is estimated as a proportion of the pan evaporation. For simplicity, it is assumed that the soil and unsaturated zone act in a manner similar to a 'leaking bucket', with recharge to groundwater occurring only when the soil moisture content is above field capacity.

The AgET model was initially used to calculate daily water balance of the BMNDRC using 1954 to 1993 Coorow and/or Dalwallinu daily rainfall data. A daily soil water balance was developed to estimate periods of wetness and drought whereby deep drainage can be simulated.

5.4.5 Predicted Runoff and Deep Flows Using AgET

There are a limited number of stream flows gauging stations in the BMNDRC. Consequently it was necessary to conduct a simulation study to estimate the rates of surface run-off and groundwater recharge under different cropping systems in a season.

AgET is a simple Water Balance Calculating program developed by the Natural Resource Management Unit, Agriculture WA and the University of Melbourne

(Argent and George, 1997). The model compares water use and recharge under different land-use rotations on different soil types. It is a bucket model and does not take into account any throughflow from neighbouring areas, only direct rainfall. This model uses average climatic data and representative soil and plant information obtained within the agricultural areas of Western Australia. Estimations of evapotranspiration (ET) are based on the Pan Evaporation Method (FAO, 1977). A pan coefficient of 0.8 is used to calculate potential evaporation from pan evaporation. AgET is not designed to cope with excessive water-logging and lateral flow and therefore has not been used to assess the valley floor flow systems. Crop coefficients for bare soil, cereal crops and native vegetation are presented on Figure 5-18. The rooting depths for bare soil, cereal crops and native vegetation are summarised in Table 5-8.

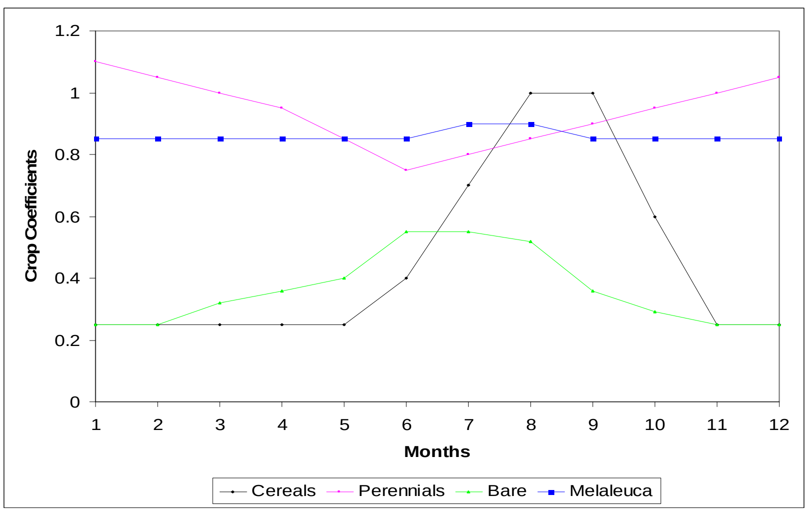


Figure 5-18 Crop coefficients used for AgET simulations

In AgET, water simply moves straight through the soil profile ignoring influences other than plant water use, evaporation and runoff. AgET also does not consider recharge associated with water-logging and preferred pathway flow. As a result, recharge on some soil types may be higher than the model suggests.

The AgET model was initially used to calculate daily water balance of the BMNDRC using Coorow and Dalwallinu daily rainfall data for the period 1954 to 1993. As the seasonal rainfall trend has changed in recent years, rainfall data sets for both Coorow and Dalwallinu were subsequently updated to capture trends from 1966 to 2006. This provided an opportunity to test the sensitivity of the model to changes in daily rainfall.

Table 5-8 Rooting Depths for Different Vegetation Types

Crops/Soil	**Rooting Depth (m)**		
	Minimum	**Effective**	**Maximum**
Bare	0.1	0.3	0.5
Cereals	0.2	0.8	1.0
Native Vegetation	2	3	8

Water use is based on leaf area index of the different crops and this closely ties to rooting depth. The daily water balance for any soil is based upon the soil moisture available over the lesser of the soil layer thickness and the effective rooting depth of the crop. Thus, if the crop or plant has roots in the A-horizon, the balance is performed on the A-horizon: any drainage from the A-horizon goes to the deep flow component. AgET takes no account of the water table and all calculations are carried out as if the water table is too deep to impact on the plants.

The basic steps in the operation of AgET each day are:

1. Determine the rainfall for the day, with allowance made for runoff from intense storms.
2. Determine ET for the day. This is dependent upon the climate (evaporation), monthly crop factor (ability of the plant to grow) and the moisture available in the soil.
3. Perform the water balance for the day by adding rainfall and subtracting ET. This also determines if there is any surface runoff, how much moisture drains into different soil levels and how much water goes to deep flow.
4. Alter the current soil moisture levels to reflect the results of the daily balance.

The water balance components of rainfall, runoff, evapotranspiration, soil storage and deep flow are summed to provide monthly and annual data. Several simulations for each soil type were investigated. Each simulation reported results for probability of exceedence representing a predicted drying climate, mean or current climate and a wet climate. Outputs from these AgET simulations are semi-quantitative. As the seasonal rainfall trend has changed in the recent past, the most representative values for the period from 1966 to 2006 were applied to final water balance estimates.

5.4.6 Deep sandy loam soil

Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths included 1.5 m deep horizon A and 1.5 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 135 mm m^{-1} with K_{sat} of 8 mm day^{-1} was used for horizon A and 195 mm m^{-1} with K_{sat} of 20 mm day^{-1} used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface runoff and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 5-9. As an example, in a wet year Coorow received 446 mm of annual rainfall from 1953 to 1993 and 437 mm of annual from 1966 to 2006. Considering simulation period from 1953 to 1993, in a wet year Coorow will observe an annual runoff of 15 mm for bare soil and 13 mm runoff for cereals and native vegetation. For simulation period from 1966 to 2006, in a wet year Coorow will observe an annual runoff of 10 mm for bare soil 7 mm runoff for cereals and 3 mm runoff for native vegetation. For 1953 to 1993 simulation period Coorow will observe an annual groundwater recharge of 186 mm for bare soil, 184 mm groundwater recharge for cereals and 69 mm of groundwater recharge for native vegetation. Similarly, for 1966 to 2006 simulation period Coorow will observe an annual groundwater recharge of 139 mm for bare soil, 47 mm groundwater recharge for cereals and 7 mm of groundwater recharge for native vegetation. The results of this simulation study indicate that in drying climate of recent years both runoff and groundwater recharge are decreasing in Coorow.

Results indicate that under current rainfall trends, up to 95% of annual rainfall is lost through ET and there is no surface runoff in dry and median years and in the wet years there is 10 to 15 mm $year^{-1}$ surface runoff is estimated. Recharge estimates range from 29% of annual rainfall for bare soil to 15% for cropped areas and 2% for native vegetation. The Indian Ocean Climate Initiative Report (2006) predicts rainfall trends will continue declining over the next 25 years. This report predicts declines in winter rainfall up to 20%. Under a continued drying climate trend, recharge may decline by 1.5% to 8%, potentially leading to lowering of groundwater levels. An increased occurrence of high intensity storms may, however, influence both recharge rates and potentials for groundwater level decline.

Table 5-9 Predicted Runoff and Deep Flows for Coorow and Dalwallinu for deep sandy loam soil

Probability of Exceedence		DEEP SANDY LOAM SOIL TYPE									
		Annual Rainfall (mm)	ET (mm/annum)			Runoff (mm/annum)			Recharge (mm/annum)		
			Bare Soil	Cereals	Native Veg.	Bare Soil	Cereals	Native Veg.	Bare Soil	Cereals	Native Veg.
Coorow Rainfall Station	Dry	317 (280)	194 (224)	277 (285)	283 (286)	0 (0)	0 (0)	0 (0)	106 (55)	58 (4)	15 (0)
	Median	389 (379)	214 (250)	306 (333)	320 (365)	2 (0)	0 (0)	0 (0)	150 (106)	114 (12)	41 (0.3)
	Wet	446 (437)	246 (279)	346 (371)	394 (395)	15 (10)	13 (7)	13 (3)	186 (139)	184 (47)	69 (7)
Dalwallinu Rainfall Station	Dry	288 (270)	190 (187)	275 (265)	271 (261)	0 (0)	0 (0)	0 (0)	85 (61)	52 (59)	6 (2)
	Median	361 (324)	224 (224)	306 (304)	315 (305)	0 (0)	0 (0)	0 (0)	117 (98)	93 (85)	20 (15)
	Wet	423 (391)	241 (241)	338 (320)	363 (343)	10 (10)	10 (10)	10 (10)	160 (143)	147 (131)	43 (35)

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

5.4.7 Sandy clay/shallow sandy duplex soil type

Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths used in the water balance simulations included 0.2 m deep horizon A and 0.8 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 100 mm m^{-1} with K_{sat} of 2 mm day^{-1} was used for horizon A and an available water of 80 mm m^{-1} with K_{sat} of 10 mm day^{-1} used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface runoff and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 5-10.

Under medium rainfall scenario, results show that more than 300 mm $year^{-1}$ representing about 77% annual rainfall is lost by evapotranspiration. As a proportion of annual rainfall, this rate increases up to about 90% with a projected drying climate. The model reported particularly little surface runoff (3 to 9%). Recharge estimations indicate significantly greater recharge under bare soils than under cereal crops. The simulation reported no recharge occurs under native vegetation.

In a medium year, recharge rates for the western areas (Coorow) range between 70 mm (18%) for bare soils compared to 34 mm (9%) for cereal crops. The dryer eastern areas (Dalwallinu) reported a lower rate of 56 mm under bare soils and 28 mm under cereal crops.

When comparing rainfall periods 1953 to 1993 and 1966 to 2006 there has been an estimated 2 to 8% decline in annual rainfall in recent times. For example, this has lead to nil recharge in bare soil areas in the western catchment area (Coorow) from 40 mm estimated in the 1953 to 1993 period. Due to the drying rainfall pattern, recharge rates in cropped areas have declined by 100%.

Table 5-10 Predicted Runoff and Deep Flows for Coorow and Dalwallinu for sandy clay/shallow sandy duplex soil type

Probability of Exceedence		SHALLOW SANDY DUPLEX SOIL TYPE									
		Annual Rainfall (mm)	ET (mm/annum)			Runoff (mm/annum)			Recharge (mm/annum)		
			Bare Soil	Cereal Crop	Native Veg.	Bare Soil	Cereal Crop	Native Veg.	Bare Soil	Cereal Crop	Native Veg.
Coorow Rainfall Station	Dry	317 (280)	206 (244)	275 (276)	283 (17)	38 (0)	34 (0)	17 (0)	42 (0)	0 (0)	0 (0)
	Median	389 (379)	239 (277)	318 (344)	335 (343)	79 (33)	73 (13)	37 (9)	70 (40)	34 (0)	0 (0)
	Wet	446 (337)	280 (305)	361 (387)	392 (393)	111 (81)	108 (59)	81 (49)	87 (55)	71 (1.5)	0 (0)
Dalwallinu Rainfall Station	Dry	288 (270)	214 (211)	272 (364)	267 (264)	16 (10)	16 (0.2)	4 (0.2)	32 (27)	0 (0)	0 (0)
	Median	361 (324)	243 (252)	318 (299)	310 (299)	51 (36)	51 (22)	32 (22)	56 (41)	28 (0)	0 (0)
	Wet	423 (391)	278 (267)	254 (259)	378 (359)	79 (64)	87 (43)	63 (43)	77 (72)	57 (0)	0 (0)

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

5.4.8 Shallow sandy duplex soil type

Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths used in the water balance simulations included 0.2 m deep horizon A and 0.8 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 80 mm m^{-1} with K_{sat} of 10 mm day^{-1} was used for horizon A and an available water of 80 mm m^{-1} with K_{sat} of 10 mm day^{-1} used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface run-off and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 5-11.

Under a medium rainfall scenario, results show that more than 300 mm year^{-1} representing about 82% annual rainfall is lost by evapotranspiration. As a proportion of annual rainfall, this rate increases up to about 86% with a projected drying climate. The model reported particularly little surface runoff (20%). Recharge estimations indicate significantly greater recharge under bare soils than under cereal crops. The simulation reported no recharge occurs under native vegetation.

Table 5-11 Predicted Runoff and Deep Flows for Coorow and Dalwallinu for shallow sandy duplex soil type

Probability of Exceedence		SHALLOW SANDY DUPLEX SOIL TYPE									
		Annual Rainfall (mm)	ET (mm/annum)			Runoff (mm/annum)			Recharge (mm/annum)		
			Bare Soil	Cereal s	Perennial Grasses	Bare Soil	Cereals	Perennial Grasses	Bare Soil	Cereals	Perennial Grasses
Coorow Rainfall Station	Dry	317 (280)	206 (244)	275 (276)	283 (17)	38 (0)	34 (0)	17 (0)	42 (0)	0 (0)	0 (0)
	Median	389 (379)	239 (277)	318 (344)	335 (343)	79 (33)	73 (13)	37 (9)	70 (40)	34 (0)	0 (0)
	Wet	446 (337)	280 (305)	361 (387)	392 (393)	111 (81)	108 (59)	81 (49)	87 (55)	71 (1.5)	0 (0)
Dalwallinu Rainfall Station	Dry	288 (270)	214 (211)	272 (364)	267 (264)	16 (10)	16 (0.2)	4 (0.2)	32 (27)	0 (0)	0 (0)
	Median	361 (324)	243 (252)	318 (299)	310 (299)	51 (36)	51 (22)	32 (22)	56 (41)	28 (0)	0 (0)
	Wet	423 (391)	278 (267)	254 (259)	378 (359)	79 (64)	87 (43)	63 (43)	77 (72)	57 (0)	0 (0)

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

5.4.9 Daily Soil Water Balance Model

A simple mathematical representation of sub-surface soil drainage and recharge is a bucket model. Bucket models are generally conceptualised as the water capacity of the root zone across the catchment. The bucket fills with infiltration and empties through evapotranspiration. Actual evaporation and soil moisture are calculated on the basis of a simple daily soil water balance. Potential evapotranspiration is estimated as a proportion of the pan evaporation. For simplicity, it is assumed that the soil and unsaturated zone act in a manner similar to a 'leaking bucket', with recharge to groundwater occurring only when the soil moisture content is above field capacity.

The AgET model was initially used to calculate daily water balance of the BMNDRC using 1954 to 1993 Coorow and/or Dalwallinu daily rainfall data. A daily soil water balance was developed to estimate periods of wetness and drought whereby deep drainage can be simulated.

A simple daily water balance (W) given in Equation 5-2 was used to calculate daily water balance by taking a soil water storage capacity (S) of 200 mm per meter area and zero respectively as upper and lower limits, rainfall (R) as input and crop evapotranspiration (ETc) as output:

$$W_n = W_{n-1} + R - ET_c \qquad (5\text{-}2)$$

So on day n, the daily water balance for the soil, (W_n) is evaluated by taking its value on the previous day, adding the rainfall on day n and subtracting the ET_c. If the result is less than zero, it is set to zero, while if it is greater than S it is set to S (corresponding to a soil profile at field capacity).

The daily water balance of Coorow from 1999 to 2005 is shown in Figure 5-19. The highest daily water balance was observed in 1999 following the significant rainfall events subsequent to tropical Cyclones Elaine and Vance in 1999. During winter season of 1999, water balance was at soil water storage capacity on several occasions and there were chances of groundwater recharge and surface water runoff. Figure 5-20 shows daily water balance and groundwater hydrograph from 1996 to 2005 for Doley. The recovery in the groundwater level after wet winter of 1999 can be seen in the rise of groundwater hydrograph. There was an 8 years delay for the water table to reach previous levels.

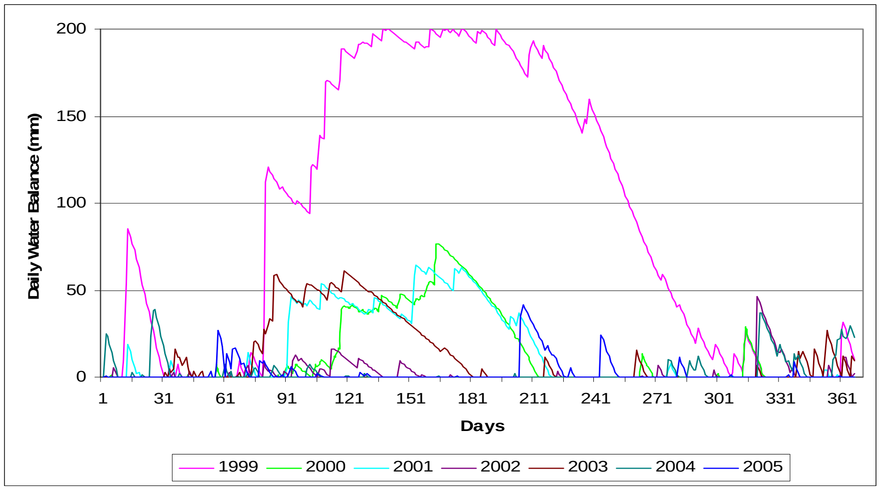


Figure 5-19 Daily water balance from 1999 to 2005 for Coorow

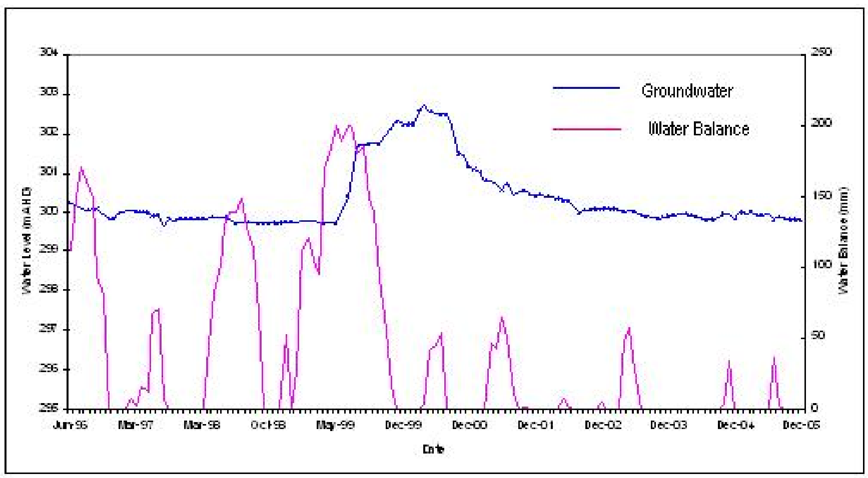


Figure 5-20 Daily water balance (red) and groundwater hydrograph (blue) from 1996 to 2005 for Doley

Seasonal rainfall trends for Coorow BOM station show a significant decline in five-year moving average winter trend. This downward winter rainfall trend would reflect lower surface runoff and recharge to the groundwater during winter. Conversely, the summer season rainfall shows an upward trend (5-year-moving average). Importantly, the increased frequency of larger summer rainfall events, occurring on a landscape that is largely devoid of vegetation, during these months is likely to result in recharge increases to the watertable.

Recharge estimates using recent rainfall data (1966 to 2006) indicate groundwater levels in Coorow and Dalwallinu catchments are likely to be declining as a result of lower rainfall and a generally drying climate. Future predictions of groundwater trends must consider that the recent decline in groundwater levels across most of the BMNDRC since 1999 may be masking a longer-term trend of rising groundwater levels. This is particularly important given the likely increased occurrence of significant rainfall events, such as those which occurred in 1917, 1963, and 1999, which may drive groundwater tables to rise.

The interpretations based on available data indicate that significant rainfall events have a strong influence on recharge and hence water table elevations. A continual change in the summer and winter rainfall trends and patterns would potentially lead to changes in water table elevations. The problem of waterlogging and soil salinisation develops when the water levels rise relatively close to the soil surface. The presence of a saline shallow water table can be a major source of soil salinity if upward flux to the root zone area is sufficient. Salts are left in the root zone as a result of evapotranspiration and can adversely affect the soil structure and limit plant growth.

5. 5 Climate Change Studies in Western Australia

In this section a climate change study will be conducted for a region influenced by tropical cyclones in the north of Western Australia. Tropical cyclones (T.C.) are formed over ocean when water temperature exceeds 27ºC in the north of Western Australia and move into the tracks towards Port Hedland and adjoining areas (Figure 5-21). A thunderstorm which is the smaller scale of a tropical cyclone is also common in the area. The Pilbara region in Western Australia is the place where maximum tropical storms move into inland areas in Australia. The storm’s wind may exceed 150 km hour^{-1} and may cause damage to buildings, vegetation and infrastructures of ports and towns in coastal areas. The low-lying coastlines are flooded by waves or surges of ocean water generated by the storm’s winds. The coastal flooding is especially severe when the storm occurs during a high-tide period. The Pilbara coast experienced six tropical cyclones in Jan. 1939, March 1942, T.C. Joan in Dec. 1975, T.C. Leo in March 1977, T.C. in Dean Feb. 1980, and T.C. Connie in Jan. 1987 (Bureau of Meteorology, 2007).

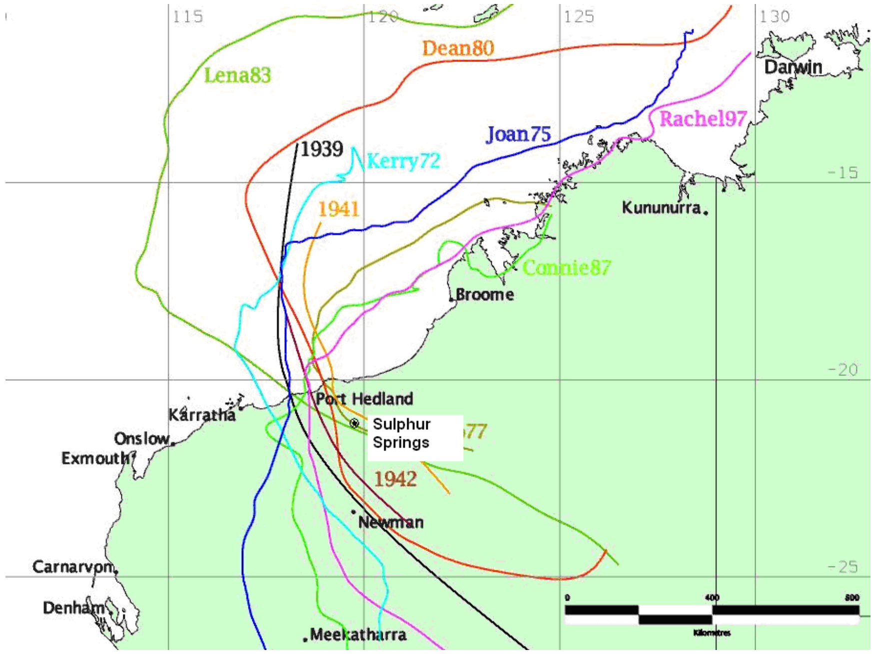


Figure 5-21 Cyclones tracks that impact Port Hedland and adjoining areas (BoM, 2007)

Rainfall totals in excess of 100 mm are common with tropical cyclones that move over land. In February 2003, a tropical cyclone moved over Port Hedland and some parts received rainfall in excess of 300 mm which caused flooding in the Yule River. The Panorama Project Site is located approximately 110 km southeast of Port Hedland. To assess if the region is experiencing climate change and the effect this may have on the water resources, the daily rainfall record for the area is analysed to identify changes in episodic rainfall events, seasonal and annual rainfall trends. As the episodic rainfall events are the most critical for this site, this assessment looks to identify cyclone patterns and changes in their frequency of occurrence.

5.5.1 Data used

The long-term daily rainfall data was obtained for Panorama site from SILO data drill of Queensland's Department of Natural Resources and Mines from 1889 to 2007. The Data Drill is a facility for extracting data from an archive of interpolated rainfall and climate surfaces maintained by the Queensland Department of Natural Resources and Mines. These surfaces were constructed by spatially interpolating observational data collected by the Australian Bureau of Meteorology. The SILO rainfall data was analysed and compared with the BoM rainfall data for Marble Bar, some 50 km east of the Panorama Mine site.

5.5.2 Episodic Rainfall Events in Marble Bar

The episodic rainfall events are experienced in Marble Bar and can cause flash floods. Maximum daily rainfall of each year of record from 1901 to 1996 and daily rainfall totals of 2-day, 3-day and 1-week durations were used to calculate episodic rainfall events. Some of these episodic rainfall events are presented in Figure 5-22. There were 6 episodic rainfall events of more than 200 mm of 1-week duration or less, 13 events of more than 150 mm and 30 events of more than 100 mm between 1901 and 1996 for Marble Bar. The Marble Bar receives a mean annual episodic rainfall event of one week duration or less of 147 mm with a standard deviation of 58 mm. Marble Bar experienced a daily rainfall of 100 mm or more on 17 occasions, more than 70 mm of daily rainfall on 47 occasions and more than 50 mm on 105 occasions between 1901 and 1996. The maximum daily rainfall of 304 mm was recorded on 3 February, 1941.

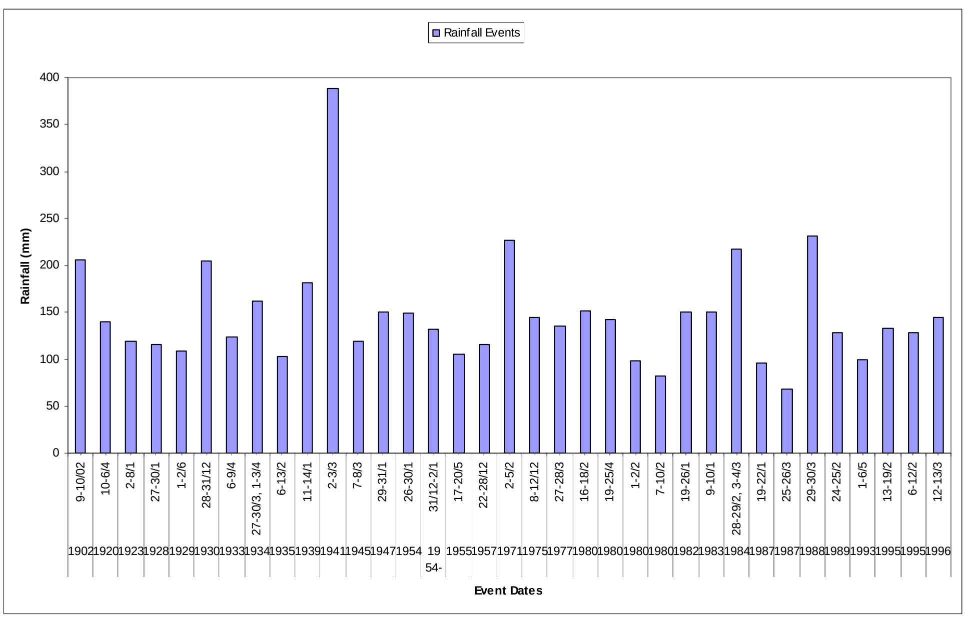


Figure 5-22 Episodic Rainfall Events for Marble Bar

5.5.3 Change in Rainfall Intensity

Actual rainfall intensities of Marble Bar were compared with rainfall intensities of Marble Bar calculated by Pilgrim (2001) methodology. Actual rainfall intensities are slightly more than the calculated rainfall intensities (Table 5-13).

Table 5-12 Actual and calculated rainfall intensities for Marble Bar

Rainfall Duration (hr)	Rainfall (mm)	Rainfall Intensity (mm hr^{-1})	ARR 100-yr ARI Rainfall Intensity (mm hr^{-1})
24	304	12.67	12
48	388.6	8.1	7.4
72	388.6	5.4	5.3

5.5.4 Rainfall Trends

The long-term daily rainfall data of Marble Bar was obtained from BoM from 1901 to 2007. Annual rainfall data for the Marble Bar suggests great annual variability. On average the site receives 351 mm with a minimum of 35 mm and a maximum of 894 mm per annum.

To determine long term changes in climate patterns the BoM uses the 30 year moving average statistic. To assess changes in climate for the long rainfall record at Marble was analysed using the 30 year moving average to detect long term trends in rainfall. Figure 5-23 shows that the 30 year moving average is increasing in the last 20 years. This means a gradual increase in annual rainfall over this period. It also shows an increasing trend which indicates further increases in the future.

To accentuate this result and bring the statistic in line with the expected life of mine, the same rainfall record was analysed using the 10 year moving average. The result is shown in Figure 5-24. It shows a similar trend of increasing annual rainfall in the last decade in particular.

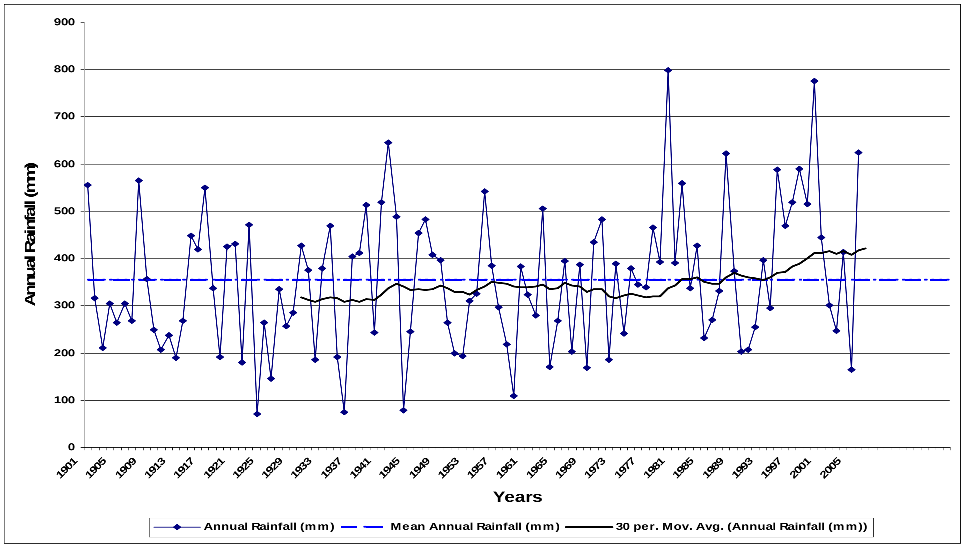


Figure 5-23 Annual Rainfall Trend with 30 Years Moving Average for Marble Bar

5.5.5 Cumulative Deviation from the Mean

The long-term annual rainfall data from 1889 to 2007 was used for Panorama site to establish cumulative deviation from the mean rainfall (CDFM). The CDFM technique shows that annual rainfall over the period from 1889 to 2007 has an upward trend since 1992 (Figure 5-25).

The next step is to determine what causes the annual rainfall to increase. This aims to determine if the annual rainfall pattern is changing or is the pattern the same but as a whole moving up. To assess this the annual summer and winter rainfall were analysed using the 10 year moving average.

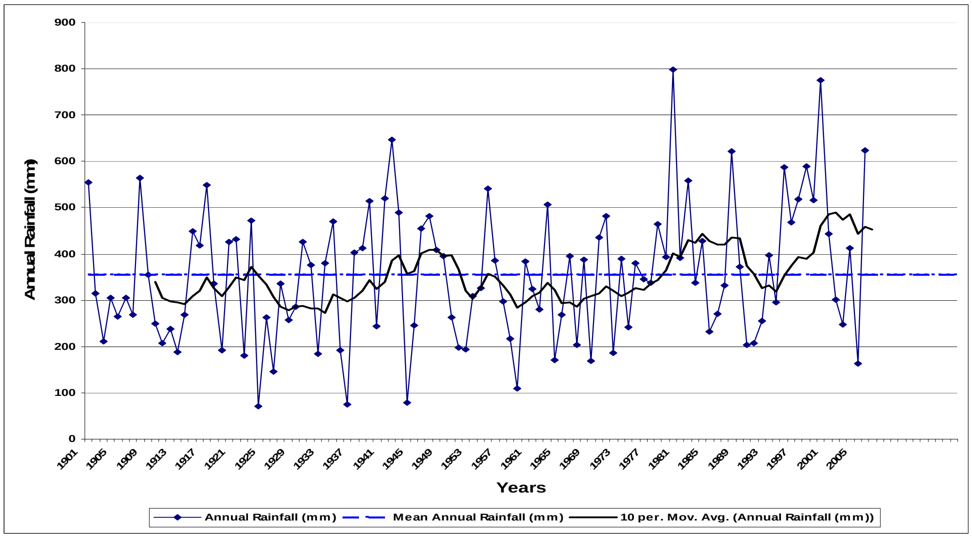


Figure 5-24 Annual Rainfall Trend with 10 Years Moving Average for Marble Bar

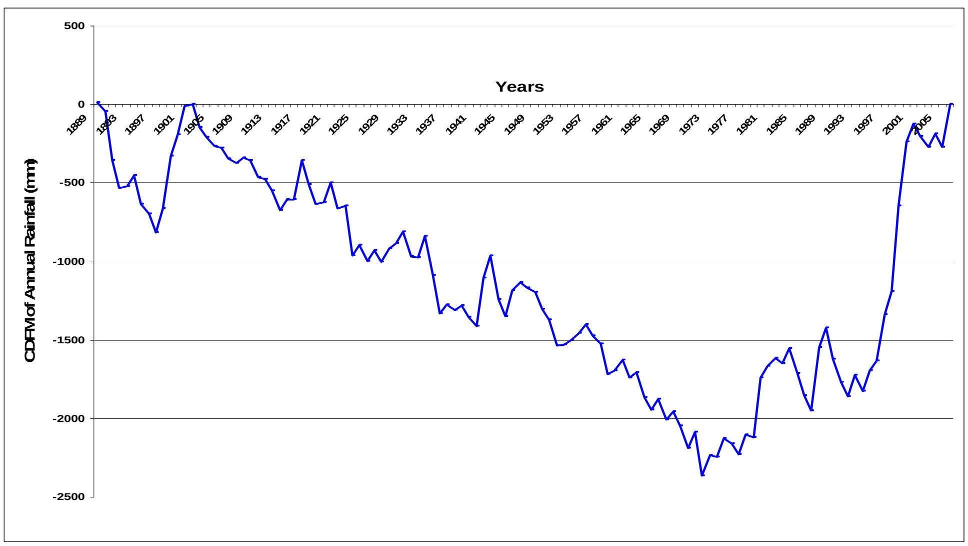


Figure 5-25 Annual Rainfall Cumulative Deviation from the Mean Rainfall (CDFM) for Panorama site

5.5.6 Summer Rainfall Trends

The summer season rainfall has been calculated by adding rainfall during November and December of first year and rainfall from January to April in the succeeding year. Summer rainfall from 1889 to 2007 has been plotted in Figure 5-26. The Panorama site receives an average summer rainfall of 274 mm. The ten year moving average trend line shows an upward trend in summer rainfall for Panorama site over the past

118 years (Figure 5-26). The summer season rainfall varies from 43 mm to 873 mm. The majority of the annual rainfall is received in the summer months of January, February and March. During 1998, 1999 and 2005, summer rainfall was more than 500 mm.

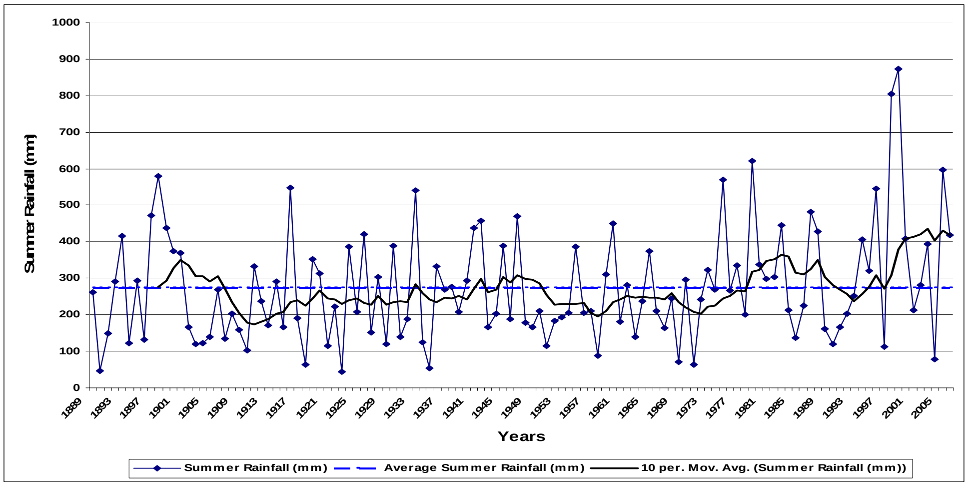


Figure 5-26 Summer Season Rainfall Trend for Panorama mine site

The long-term summer rainfall data from 1889 to 2007 was used for Panorama site to establish cumulative deviation from the mean rainfall (CDFM). The CDFM technique shows that annual rainfall over the period from 1889 to 2007 has an upward trend since 1992 (Figure 5-27).

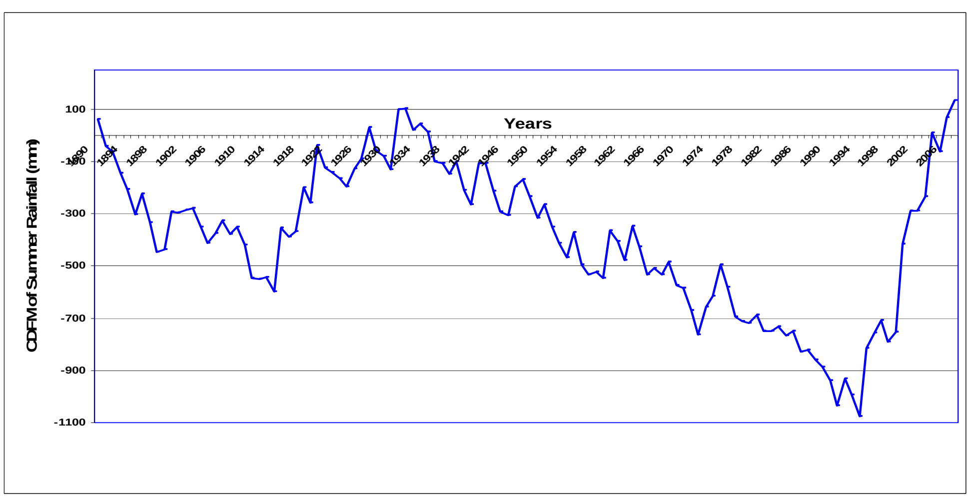


Figure 5-27 Summer Rainfall Cumulative Deviation from the Mean Rainfall (CDFM) for Panorama

5.5.7 Winter Rainfall Trends

Winter rainfall ranges from 1 mm to 267 mm. On average the Panorama site receives 79 mm from May to October. Winter season rainfall from 1889 to 2007 has been plotted in Figure 5-28. During 1997, 1998 and 2005, winter rainfall was more than 150 mm compared the mean winter rainfall of 79 mm.

The ten year moving average trend line shows an upward trend in the winter rainfall received by Panorama minesite over last 118 years (Figure 5-28). The long-term winter rainfall data from 1889 to 2007 was used for Panorama site to establish cumulative deviation from the mean rainfall (CDFM). The CDFM technique shows that annual rainfall over the period from 1889 to 2007 has an upward trend since 1992 (Figure 5-29).

5.5.8 Changes in Mean Annual Rainfall

Figure 5-30 shows that the Mean annual rainfall of 360 mm for the Panorama Site is derived from 100 year long rainfall record, of which the first 75 years were well below this average, hence the increasing cumulative negative variance, and a 25 year period of higher than mean annual rainfall. The figure suggests three periods. The period prior to 1975, with below average rainfall, the period between 1975 and 1990 with above average rainfall and the period from 1990 with higher average rainfall than the period before. The average annual rainfall for these three periods is shown in Figure 5-30. The average annual rainfall for the past 10 decades is given in the Table 5-13. The 1st decade has annual rainfall data from 1897 to 1896 only. The maximum annual decadal rainfall for Panorama minesite was between 1997 and 2006.

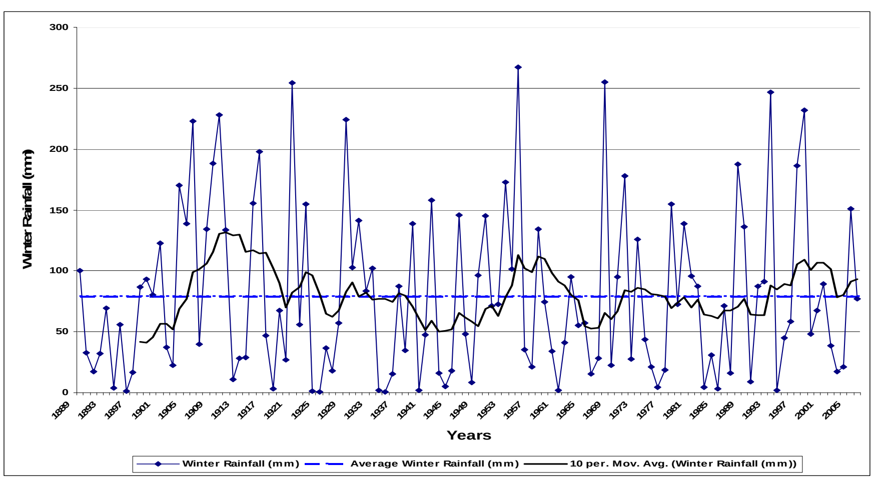


Figure 5-28 Winter Season Rainfall Trend for Panorama mine site

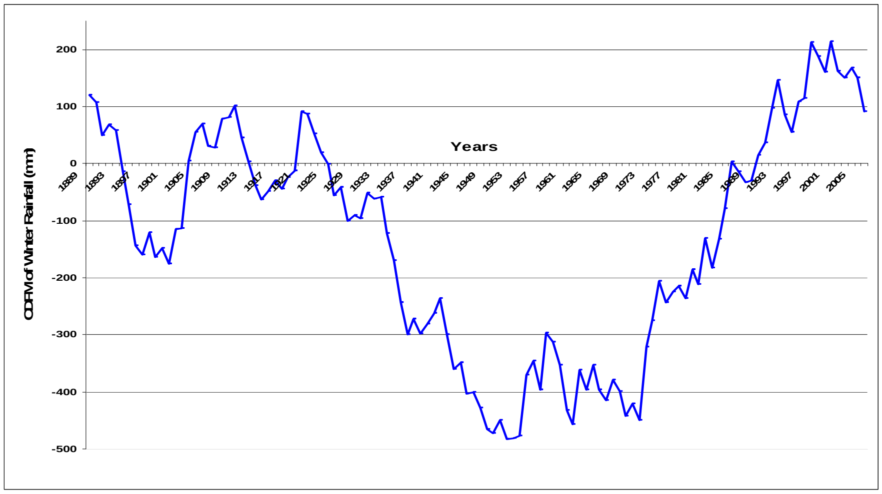


Figure 5-29 Winter Rainfall Cumulative Deviation from the Mean Rainfall (CDFM) for Panorama site

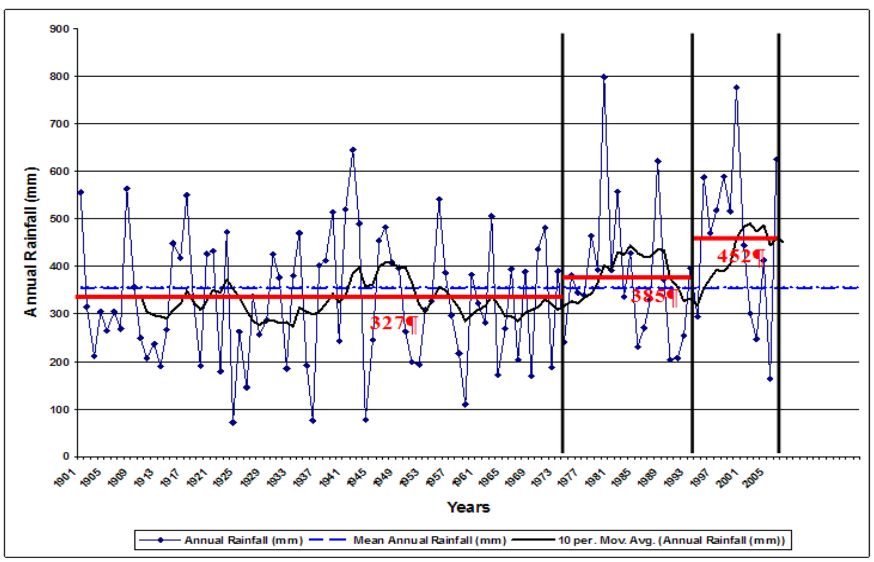


Figure 5-30 Mean Annual Rainfall for three identified rainfall periods

Table 5-13 Annual decadal rainfall for Panorama minesite

Years	Average Rainfall (mm)
1897-1906	394
1907-1916	318
1917-1926	312
1927-1936	318
1937-1946	366
1947-1956	330
1957-1966	304
1967-1976	306
1977-1986	323
1987-1996	374
1997-2006	505

5.5.9 Conclusions

Mean annual rainfall in the Panorama minesite area has increased since 1975. The annual rainfall for the region is characterized by three rainfall periods: up to 1975 the mean annual rainfall was 325 mm, between 1975 and 1990 the mean annual rainfall was 385 mm and since 1990 the mean annual rainfall his 425 mm.

Cyclones appear to occur more frequently. This means that episodic high rainfall events may occur more frequently. However, increased frequency of occurrence does not mean increased intensity. The data does not show an increase in higher intensity events. The 30-year moving average of annual rainfall of Marble Bar from 1901 to 1996 showed that the annual rainfall has increased in the last 20 years. The maximum annual decadal rainfall for Panorama minesite was between 1997 and 2006. The CDFM technique shows that annual rainfall over the period from 1889 to 2007 has an upward trend since 1992. The ten year moving average trend line shows an upward trend for both summer and winter season rainfall for Panorama site over the past 118 years.

5. 6 **Climate Change Studies in the South West of Western Australia**

The climate in south-west coastal cities of Western Australia is of Mediterranean type with hot summers and cool wet winters. Rainfall is the main source of surface runoff and recharge to groundwater systems. McFarlane (2005) has reported that since 1975, the May to July rainfall for the South West has abruptly decreased by about 15%. The absence of very wet years has resulted in greatly reduced runoff and recharge.

5.6.1 Annual Rainfall Trends in Coastal Districts of South West

The long-term annual rainfall data from 1877 to 2007 of three large coastal cities in Western Australia - Perth, Bunbury and Albany were analysed to establish cumulative deviation from the mean rainfall (CDFM). The average annual rainfall for Perth is 819 mm with a minimum annual rainfall of 480 mm (in 1914) and a maximum rainfall of 1312 mm (in 1926) from 1877 to 2007 (Figure 5-39). The CDFM analysis for Perth shows a dry period from 1877 to 1914, a wet period between 1915 and 1968, and a dry period from 1968 to 2007 (Figure 1). The CDFM technique shows that annual rainfall from 1877 to 2007 has a downward trend since 1968 for Perth (Figure 5-39). Yesertener (2005) also analysed Perth's data and found similar dry and wet periods. The long dry period since 1968 shows a climate change in Perth.

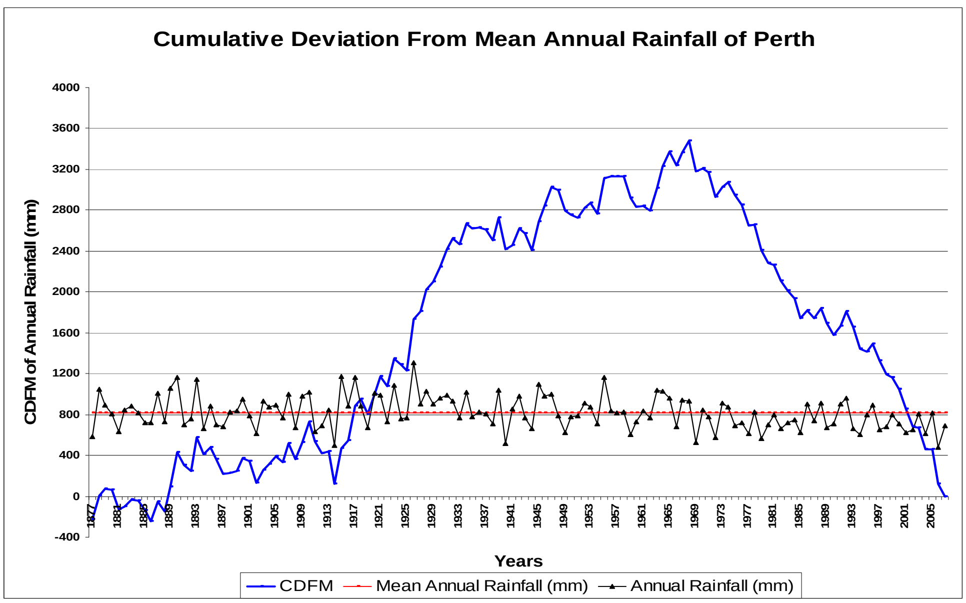


Figure 5-31 Cumulative deviation from mean (CDFM) with annual rainfall from 1877 to 2007 for Perth

The average annual rainfall for Bunbury is 843 mm with a minimum annual rainfall of 484 mm and a maximum rainfall of 1,364 mm from 1877 to 2007 (Figure 5-32). The CDFM analysis for Bunbury shows a wet period from 1881 to 1928, a dry period between 1929 and 1941, a wet period from 1942 to 1974 and a dry period from 1975 to 2007 (Figure 5-32).

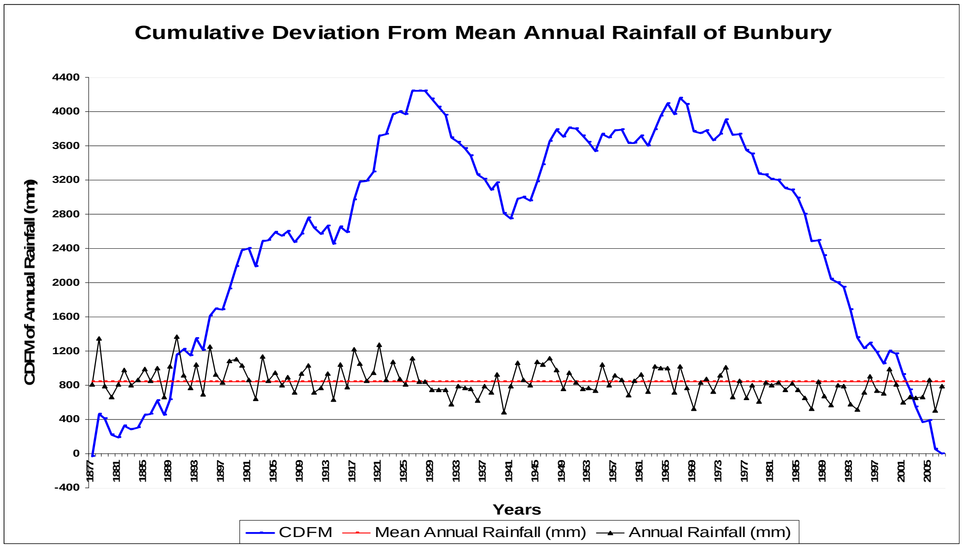


Figure 5-32 Cumulative deviation from mean (CDFM) with annual rainfall from 1877 to 2007 for Bunbury

The average annual rainfall for Albany is 929 mm with a minimum annual rainfall of 629 mm and a maximum rainfall of 1396 mm from 1877 to 2007 (Figure 5-33). The CDFM analysis for Albany shows a dry period from 1910 to 1914, a wet period between 1915 and 1968, and generally a dry period from 1969 to 2007 except two wet periods from 1975 to 1979 and 1987 to 1992 (Figure 5-33).

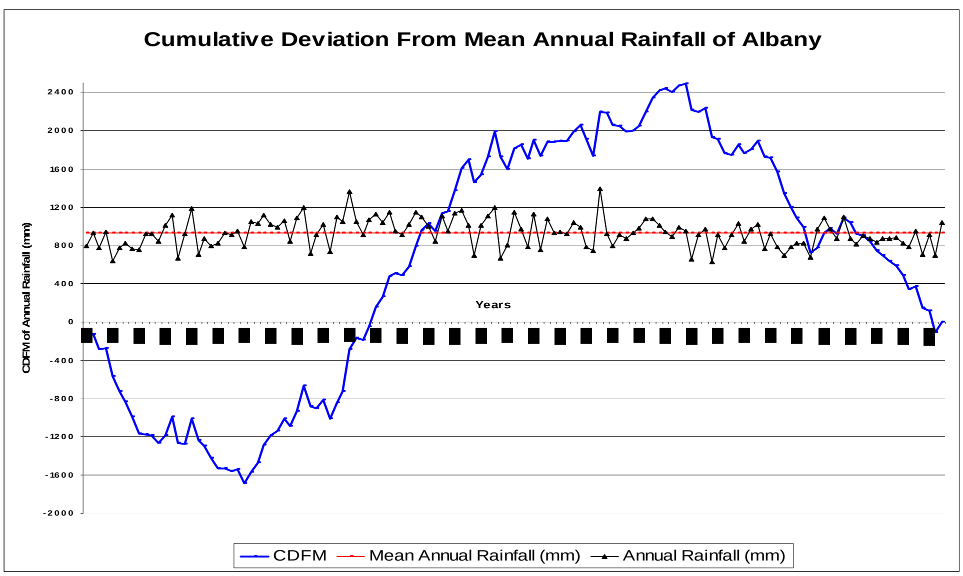


Figure 5-33 Cumulative deviation from mean (CDFM) with annual rainfall from 1877 to 2007 for Albany

Perth and Bunbury receive 85% of mean annual rainfall in winter months from May to October and Albany receives 75% of rainfall in winter months. Mean annual pan evaporation in Perth is 2081 mm, in Bunbury 1399 mm, in Albany 1387 mm. Mean annual rainfall in Perth is about 40% of the mean annual pan evaporation, 60% in Bunbury and 67% in Albany. Mean monthly rainfall in the winter months from May to September generally exceeds evaporation. Rainfall is the main source of surface runoff and recharge to groundwater systems. The low annual rainfall in recent years will result in low groundwater recharge and low discharge in streams, rivers and drainage channels.

Climate change of some of the other cities in the south-west of Western Australia have been summarised in the following section.

5.6.1.1 Mandurah

The average annual rainfall for Mandurah is 869 mm with a minimum annual rainfall of 475 mm and a maximum rainfall of 1304 mm from 1890 to 2007 (Figure 5-34). Mandurah receives 86% of and mean annual rainfall in winter months from May to October. Mean annual pan evaporation in Mandurah is 1539 mm. Mean annual rainfall in Mandurah is 57% of mean annual rainfall.

The CDFM analysis for Mandurah shows two wet periods from 1902 to 1910 and from 1916 to 1934, a mix of dry and wet periods between 1935 and 1973 and a generally dry period from 1974 to 2007 (Figure 5-34).

5.6.1.2 Pinjarra

The CDFM analysis for Pinjarra shows a wet period from 1888 to 1968, two periods of dry periods from 1910 to 1914 and 1935 to 1944 and a dry period since 1968 (Figure 5-35).

5.6.1.3 Pinjarra

The CDFM analysis for Pinjarra shows a wet period from 1888 to 1968, two periods of dry periods from 1910 to 1914 and 1935 to 1944 and a dry period since 1968 (Figure 5-35).

5.6.1.4 Pinjarra

The CDFM analysis for Pinjarra shows a wet period from 1888 to 1968, two periods of dry periods from 1910 to 1914 and 1935 to 1944 and a dry period since 1968 (Figure 5-35).

5.6.1.5 Yarloop

The CDFM analysis for Yarloop Post Office Composite shows a dry period from 1910 to 1914, two wet periods from 1914 to 1935 and from 1944 to 1950, a mix of dry and wet periods between 1951 and 1995 and a dry period from 1996 to 2007 (Figure 5-37).

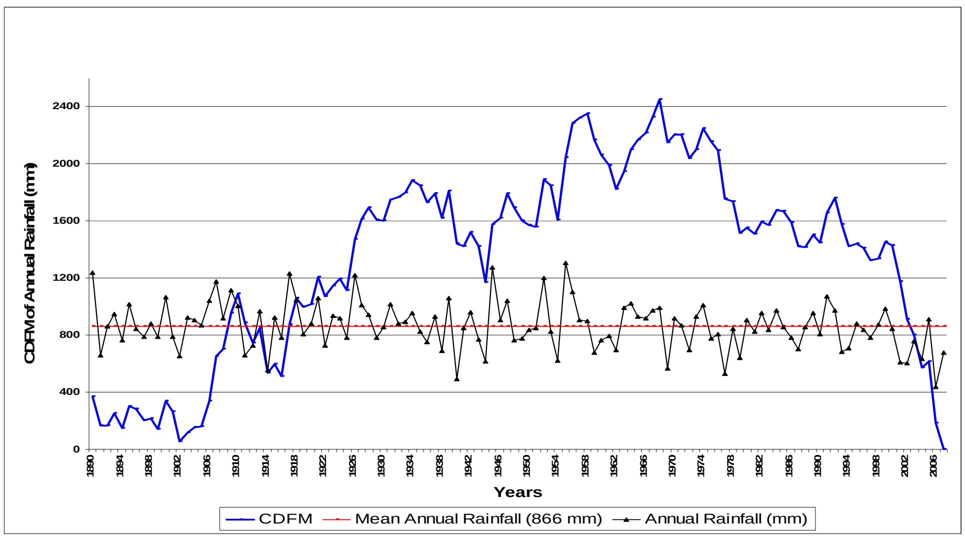


Figure 5-34 Cumulative deviation from mean (CDFM) with annual rainfall from 1890 to 2007 for Mandurah

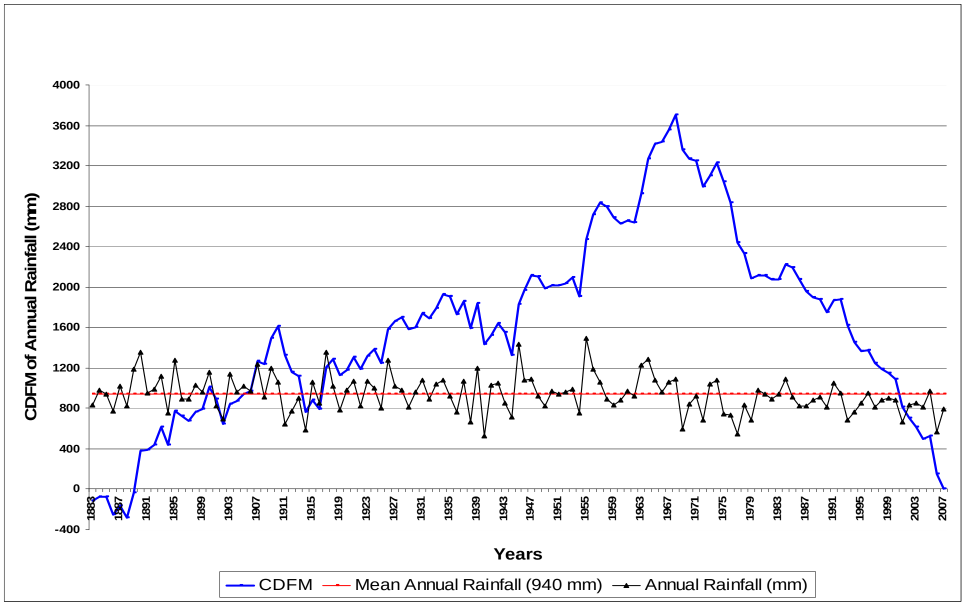


Figure 5-35 Cumulative deviation from mean (CDFM) with annual rainfall from 1883 to 2007 for Pinjarra

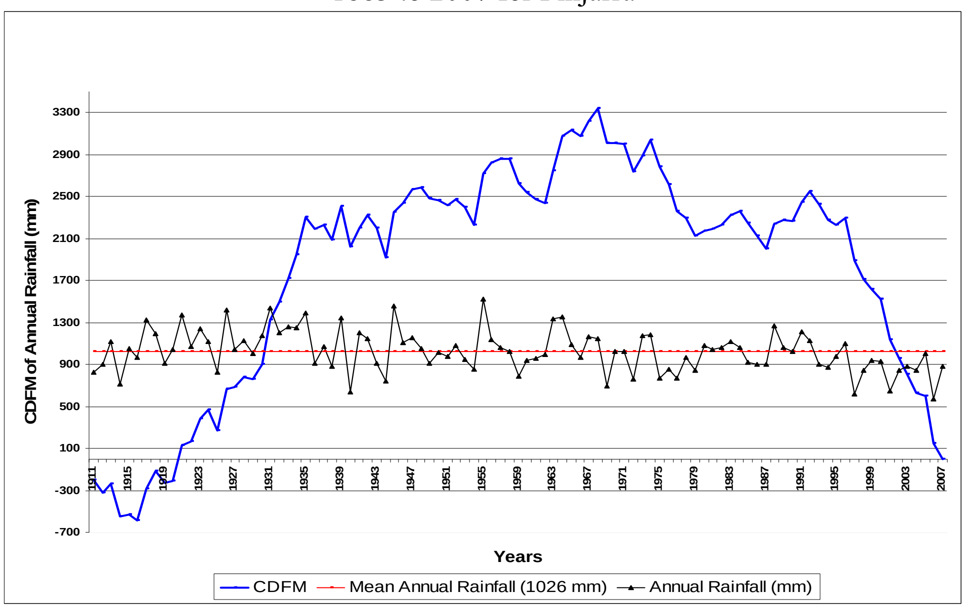


Figure 5-36 Cumulative deviation from mean (CDFM) with annual rainfall from 1911 to 2007 for Waroona

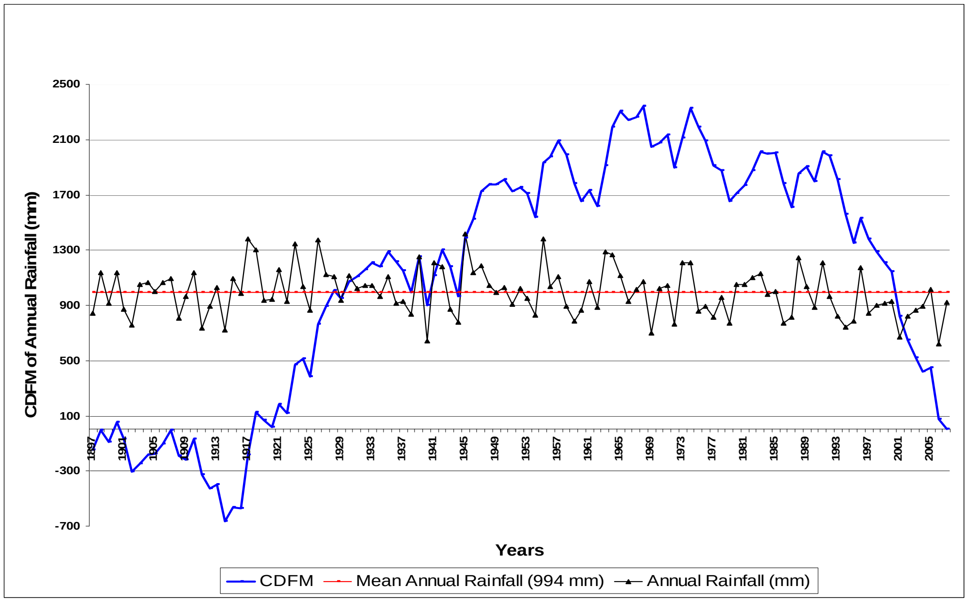


Figure 5-37 Cumulative deviation from mean (CDFM) with annual rainfall from 1897 to 2007 for Harvey (Yarloop Post Office Composite)

5.6.1.6 Harvey

The CDFM analysis for Harvey (Parkfield) shows three wet periods from 1914 to 1928, from 1944 to 1947 and from 1962 to 1967. Figure 5-38 shows a downward trend in annual rainfall since 1974 has for Harvey (Parkfield).

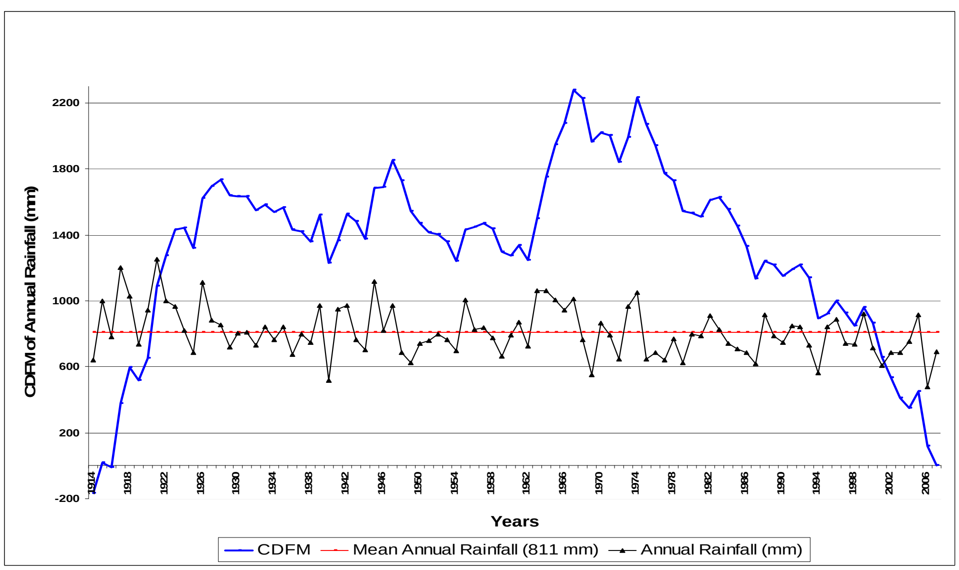


Figure 5-38 Cumulative deviation from mean (CDFM) with annual rainfall from 1914 to 2007 for Harvey (Parkfield)

5.6.1.7 Collie

Collie receives 84% of mean annual rainfall in winter months from May to October. Mean monthly rainfall in the winter months from May to September generally exceeds evaporation. Water use by vegetation i.e. trees, bushes, grasses, annual crops and pastures, is the lowest when rainfall is the highest. Low water use means that rainfall can infiltrate past the root zone to recharge the watertable. By the time the annual plants are into maximum water use between September and November, most recharge has already occurred.

It is the extreme rainfall events that often result in groundwater recharge. The rainfall events of 50 mm and 100 mm over seven and 15 successive days saturate the soil profile to result in significant aquifer recharge. Smaller or more sporadic rainfalls are mostly lost to evapotranspiration and surface runoff and contribute little to aquifer recharge. Daily rainfall data of Collie from 1904 to 1994 were analysed to calculate probabilities of rainfall events. There is a 87% probability or chance that Collie will experience 6 rainfall events of 50 mm in seven days duration in a year and 95% probability of 8 rainfall events of 50 mm in 15 days duration in a year. There is a 74% probability that Collie will experience 1 rainfall event of 100 mm in seven days duration in a year and 79% probability of 3 rainfall events of 100 mm in 15 days duration in a year.

Collie experienced very wet May during 2005 and August during 2006 when monthly rainfall totals were 229 mm and 247 mm which are more than 90th percentile (Figure 5-39). Monthly rainfall total in July, 2006 was 249 mm which was more than 80th percentile. The 2007 year was the wettest year since 1929 with several cyclonic events resulting in large monthly rainfall totals. The total rainfall for the year was 727 mm that is 2.6 times the long-term average of 279 mm.

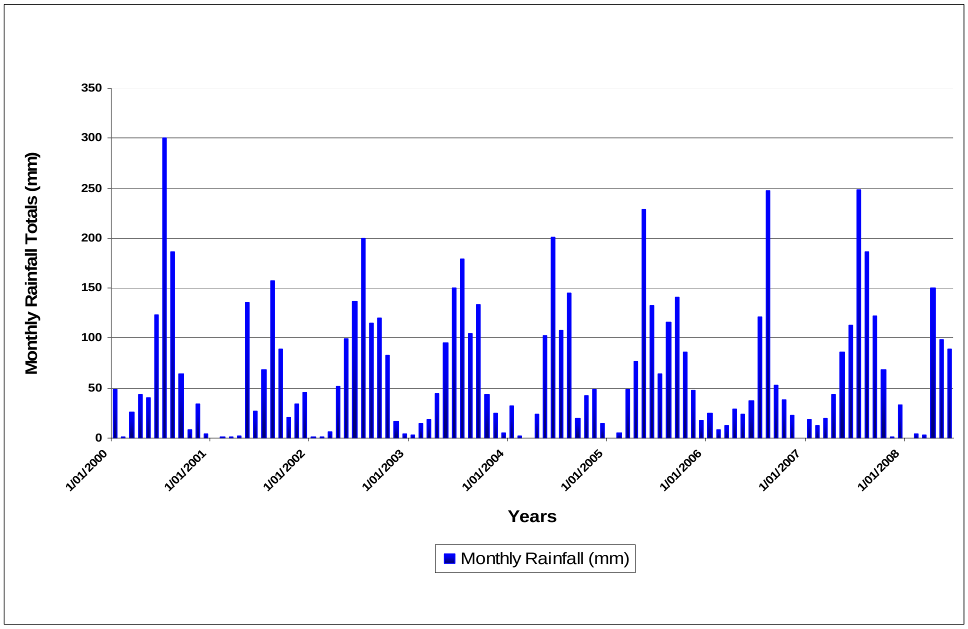


Figure 5-39 The monthly rainfall totals for Collie from 2000 to 2008

The mean annual rainfall for Collie is 940 mm with a minimum annual rainfall of 582 mm and a maximum rainfall of 1467 mm from 1899 to 2007. The mean annual evaporation for Collie is 1,724 mm. The long-term annual rainfall data from 1899 to 2007 of Collie have been plotted with mean annual rainfall in Figure 5-40. The annual rainfall data were used to establish cumulative deviation from the mean rainfall (CDFM). The CDFM analysis for Collie shows a wet period from 1916 to 1947, a mix of dry and wet periods from 1948 to 1974 and a drying trend since 1975 (Figure 5-40).

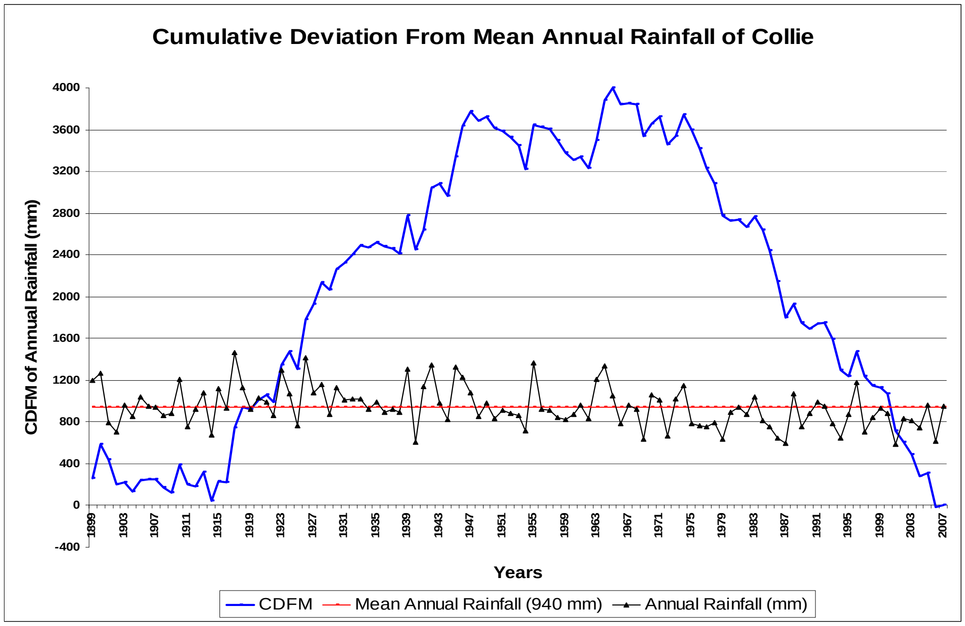


Figure 5-40 Cumulative deviation from mean (CDFM) with annual rainfall from 1899 to 2007 for Collie

The rainfall data analysis of all cities in the south-west of Western Australia indicate that annual rainfall has a decreasing trend since 1969 for some cities in the region and rainfall is decreasing in some cities since 1975. IOCI (2004) also had the similar finding that the May to July rainfall for the South West abruptly had decreased by about 15% after 1975.

5.6.2 Extreme events

Temperate fruit and nut trees have chilling requirement to flower and fruit which can be calculated by calculating number of hours when air temperature is below zero or a base temperature e.g. 7°C for apples, walnuts and almonds. An analysis of past daily maximum and minimum temperature trends with climate change scenarios of increase of 1, 2 and 3°C of minimum air temperature can indicate potential threat that climate change poses to fruit and crop production. Temperature above 30°C and 35°C depress wheat yields and flour quality. The growing degree days which is the summation of mean temperature above a base temperature e.g. 5°C for wheat are calculated to determine the length of the growing season of crops. Air temperature data of cities in the region can be analysed to determine the change in the growing season lengths of crops in the past and future scenarios of growing season lengths can be generated with climate change scenarios of increase of 1, 2 and 3°C of maximum and minimum air temperatures.

5.6.2.1 Frosts

Frosts can cause serious losses to agricultural crops and plants. A minimum temperature of 2°C in the thermometer screen will generally correspond to a light frost, whereas 0°C in the screen implies a heavy frost and when temperature falls to -2°C or lower killing frost occurs. Dates of the first and last occurrences of minimum temperature of 2°C and 0°C for Katanning for each year from 1961 to 2000 were calculated and then computed the probabilities of their occurrence. There is a 20% probability that a minimum temperature of 2°C or less (light frost) will occur on or before May 21 and there is a 80% chance that such a temperature will last until October 24. Similarly, there is a 20% probability that Katanning will experience heavy frost (0°C temperature) on or before June 13 and there is a 80% probability that it will last until September 18. The average duration of the light frost is 115 days and the average duration of the heavy frost is 67 days for Katanning. Katanning had a minimum temperature of 2°C or less in 100% of years, 0°C or less in 75% of years and a minimum temperature of -2°C or less occurred only in 1% of the years. There is a 50% probability that Katanning will experience 13 days with daily minimum temperature of 2°C or less and 2 days with 0°C or less in a season. Katanning had a maximum of 28 days with daily minimum temperature of 2°C or less and 13 days with 0°C or less in a season. Frequency and severity of frosts in any region can be determined using historic minimum temperature data and impacts of climate change on occurrence of frost in the region can be analysed. A severe frost was experienced in winter of 2001 in the valley floors of eastern Wheatbelt that resulted in no seeds in the ears of wheat or seed numbers were very low and wheat was harvested for making hay and feeding to animals.

Optimum date for planting winter crops in Katanning was determined when daily soil water balance reaches 20 mm by taking daily rainfall from 1951 to 1993 as input and daily potential evapotranspiration as output of the model. Mean date for planting of winter crops in Katanning was determined 19 May (± 23 days). The end of the growing season was defined as the day when daily soil water balance was less than 0.5 mm. The mean length of the growing season for winter crops in Katanning was

181 days (± 27days). If start of rains is delayed sowings of winter crops are delayed and fields will be exposed to wind and water erosion.

5.6.2.2 Droughts and Floods

Droughts and floods are normal and recurrent features of climate of Western Australia. Farmers in WA experienced severe droughts in 1987 and 2002 that resulted in low stream discharges and low groundwater levels and floods in 2000 that resulted in rapid increase in discharge in rivers and streams and high groundwater levels. Wind erosion causes land degradation during droughts when sandy and duplex soils have low vegetation cover. During heavy rainfalls water erosion and soil sealing and crusting are the major soil degradation processes. Stream salinisation is also a major problem in south-west WA. Less than 50% of the divertible surface water resources remain fresh (Western Australian Water Resources Council, 1986). One of the reasons for stream salinisation is overflow of hyper-saline water from a lake in an event of a major flood. During the 1955 flood, Lake Dumbleyung overflowed and the water in the Blackwood River became saltier (Siddiqi and Brockman, 2002). Prior to the 1955 flood there were mussels in the Blackwood, livestock were watered on the river, water was used for irrigating orchards and build up of algae did not occur. The 1955 flood permanently decreased the water level in Lake Dumbleyung, local residents recall erosion on the western side of the lake.

Hatton (2002) reported that after an episodic rainfall from 100 mm to 172 mm in the Avon River catchment on 21-22 January 2000, high river levels were experienced from Lake King to Perth. Much of the mainstream Avon River upstream of Northam and the Salt River upstream of Yenyenning had flows in excess of 150 m^3s^{-1} and below Northam in excess of 200 m^3s^{-1}. The volume of water reaching the Swan River during the event was 270 GL (the approximate Swan-Canning estuary volume is 50 GL). The salinity of the Swan River at the Narrows Bridge reduced from its normal 24,000 mg L^{-1} TDS prior to the event to 4,400 mg L^{-1} at peak flow. This event was the first time that the Lockhart sub-catchment had flowed significantly in summer for forty years; even during winter, this system does not usually generate any flow that reaches the Avon.

Figure 5-41 Avon River in flood on 21/22 January, 2000 (Photo, DoW)

Between 1975 and 1996, Water Corporation gauging has shown that rainfall decreased by 14% and runoff into Perth dams decreased by 48%. Since 1997, the rainfall has declined by 21% and the runoff has been 64% less than the long-term average. In the four years since 2001, rainfall was 36% less and runoff 88% less. Avon River flood of 21/22 January, 2000 is shown in Figure 5-42.

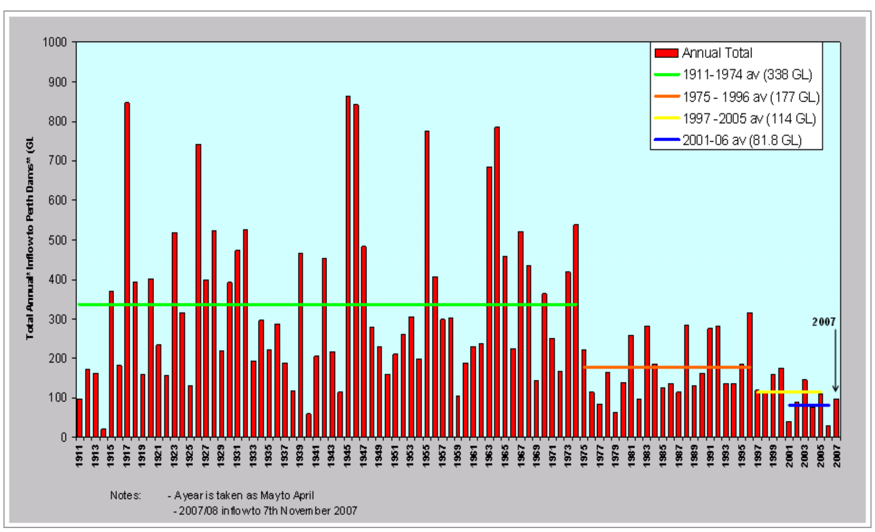


Figure 5-42 Water Corporation, Yearly Streamflow for Major Surface Water Sources (http://www.watercorporation.com.au/D/dams_streamflow.cfm)

5. 7 **Conclusions**

Rainfall is the main source of surface runoff and recharge to groundwater systems. The Water Corporation envisages a water consumption of 155 kL per capita per year and the average yield of existing sources of supply to the Integrated Water Supply Scheme (IWSS) are estimated at 256 GL per year. This comprises of 136 GL per year from surface water sources and 120 GL per year from groundwater sources.

The low annual rainfall in recent years will result in low groundwater recharge and low discharge in streams, rivers and drainage channels. Water Corporation gauging has shown that since 1997, the rainfall has declined by 21% and the runoff has been 64% less than the long-term average. In the four years since 2001, rainfall was 36% less and runoff 88% less.

The CDFM analyses of major cities of Western Australia show a long term decrease of rainfall and the effects of this climate change will be visible in times to come. Long-term monitoring of groundwater levels and surface water reserves in different areas of WA is required to see the impacts of climate change on them. The rainfall data analysis of all cities in the south-west of Western Australia indicate that annual rainfall has been decreasing since 1969 for some cities in the region and rainfall is decreasing in some cities since 1975. The winter season rainfall shows a downward trend and summer season rainfall shows an upward trend linked to an increase in the frequency of summer storm events in the south-west, in the Wheatbelt and in the east of Western Australia.

The annual rainfall and summer season rainfalls have been increasing in the north of Western Australia and both annual rainfall and summer season rainfalls an increasing trend. This increasing trend in annual rainfall and summer season rainfalls implies that there is potential risk of flooding in northern coastal towns in the future and damage to infrastructure, disruption in mining activities, and land degradation in the coastal towns and inland areas will be increase due to climate change. Farmers rely on winter rains for growing crops and pastures and water storages in farm dams and tanks for animal consumption during summer months. The decrease in winter rainfall will result in low crop yields and shortage of drinking water for humans and livestock.

6 MONITOING OF DRAINAGE NETWORK IN COASTAL DISTRICTS OF WESTERN AUSTRALIA AND DEVELOPMENT OF BMP TOOLBOX

6. 1 Scope of Development of BMP Toolbox

The objectives of this study are to review literature on monitoring of drains in coastal and inland areas in Western Australia, collate information from Australia and other countries on drainage best management practices (BMPs) and develop a 'BMP Toolbox' that will facilitate stakeholders to identify and understand technical, installation, social, economic and environmental aspects of the BMPs. This will allow stakeholders to make informed decisions as to when and what BMPs are appropriate to their needs. Identify and build up a complete list of information and data of BMPs including costing, technical data that provide proof that BMPs work and triple bottom line information

ArcView GIS was used to prepare a map of Peel Harvey, Leschenault, Vasse Wonnerup and Torbay estuaries and rivers of six drainage districts of the study area in Western Australia (Figure 6-1). The Blackwood River with a catchment area of 22,550 km^2 is the longest river in the south-west of WA and it has four major tributaries: Arthur, Coblinine, Beaufort and Balgarup Rivers. The Peel Harvey Estuary with Murray, Serpentine and Harvey River catmints have a total catchment area of 12,070 km^2.

6.1.1 Legislation and Policies

The following are some of the Common and Statute Law relating to drainage [from Gardner (1999) and Pen *et al*., (1999)]

6.1.2 Common Law

'A person is liable for causing a nuisance or harm to another person in their enjoyment of the land, by an indirect and sustained interference from an unreasonable use of the land, whether that interference is intentional, negligent or accidental or in breach of 'duty of care'. Where pollution is concerned, Part III of the Environmental Protection Act preserves the common law right to prevent, control and abate pollution.

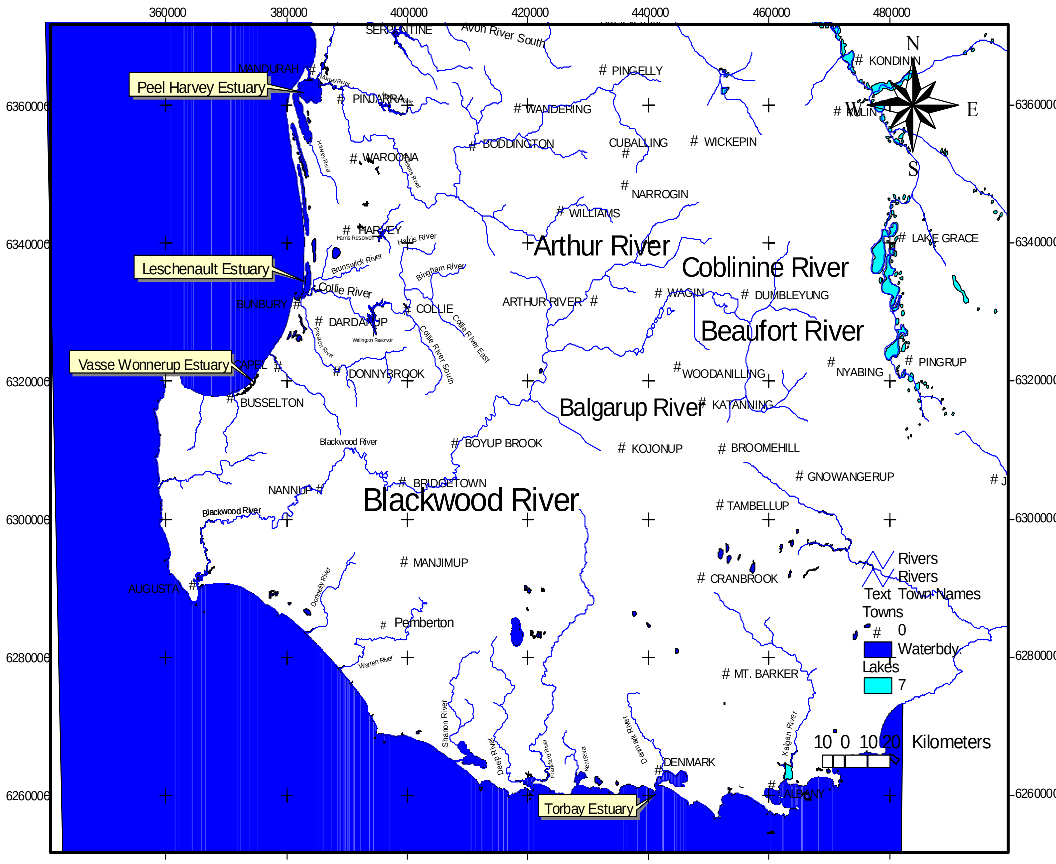


Figure 6-1 Location of estuaries, rivers and six drainage districts of the study area

6.1.3 Riparian Rights and Drainage

Landholders whose land is connected to a watercourse have a 'riparian right' to draw water, so long as it does not 'sensibly' diminish the flow. This right pertains to natural watercourses only. 'Changes to the bed and banks of a watercourse that alter its flow and cause damage to lower riparian owners may constitute an infringement of the riparian right'. 'It is arguable that the artificial discharge of saline water into a watercourse (whether by pumping or drainage) that changes the quality of water would be a breach of the riparian right to receive the flow of water undiminished in quality'. However, this is subject to 'reasonable drainage', which does not include water from another catchment or a major increase in flow from a natural lake.

6.1.4 Statutory Law

In addition there are many Statutory Laws that applies or could apply to drainage, including:

- Rights in Water and Irrigation Act (1914)

- Land Drainage Act 1925
- Soil and Land Conservation Act (1945)
- Waterways Conservation Act (1976)
- Water Agencies (Powers) Act 1984 and the Land Drainage Act 1925
- Town Planning and Development Act
- Environmental Protection Act (1986) / Environmental Protection Policy
- Local Government Act 1995
- Conservation and Land Management Act
- Wildlife Conservation Act
- Aboriginal/Heritage Act

The Rights in Water and Irrigation Act 1914 was amended in 1984 to give the Water Authority the power to prohibit drainage works that were likely to affect the water in a watercourse, wetland or underground water source. However, this power has rarely, if ever, been used in relation to rural drainage.

The Soil and Land Conservation Regulations 1992 provided the Commissioner of Soil and Land Conservation with the responsibility for assessing and approving drainage. This applied predominately to drainage that would drain subsurface water with the aim of controlling salinity and did not apply to the majority of drainage on the coastal plains. However, under Regulation 6 it did include any drainage in the Peel–Harvey Catchment and therefore did have an impact on the Mundijong, Waroona and Harvey Drainage Districts (URS, 2004).

6.1.5 Introduction of Coastal Drainage

The first drainage channel was constructed in1848 to deal with flooding from Lake Kingsford to Claisebrook. In the early 1900s, the delineation was made between ‘urban’ and ‘rural’ drainage with the proclamation of the Land Drainage Act 1900 and later the Water Supply, Sewerage and Drainage Act 1912. During this time, the Public Works Department managed and constructed drainage in parallel with the expansion of urban and rural land use. This department was eventually split into urban (metropolitan) and rural (country) areas in 1921 (Meinck, undated).

The Public Works Department continued to expand drainage in the rural areas alongside the development of irrigation areas. Through the Rights in Water and Irrigation Act 1914, Irrigation Districts could be proclaimed. These incorporated open irrigation channels and the Public Works Department was instrumental in developing and managing them (Powell, 1998).

The purpose of drainage was to provide a mechanism to control the level of seasonal inundation of arable areas throughout the year. As such, drainage channels were designed to convey larger surface flows and reduce flooding that followed the more frequent and heavier winter rains. Removing the excess surface water created a number of benefits. The main benefit was improved crop and pasture production with associated benefits of preventing salinisation associated with irrigation, reducing agricultural disease and improving machinery and vehicle access.

6.1.6 Coastal Drainage

There are six Drainage Districts, declared under the Land Drainage Act 1925, which are covered by four regional areas. The six Drainage Districts are Mundijong, Waroona, Harvey, Roelands, Busselton and Albany. Five out of the six Drainage Districts in south Western Australia are on the Swan Coastal Plain, with one being on the south coast near Albany (Figure 6-2). The Swan Coastal Plain extends from Guilderton (60 km north of Perth) to Dunsborough (300 km south-west of Perth). The Swan Coastal Plain originated from a combination of marine, aeolian (wind) and alluvial (river) deposited materials and consists of three basic geomorphic units (WAWRC, 1992).

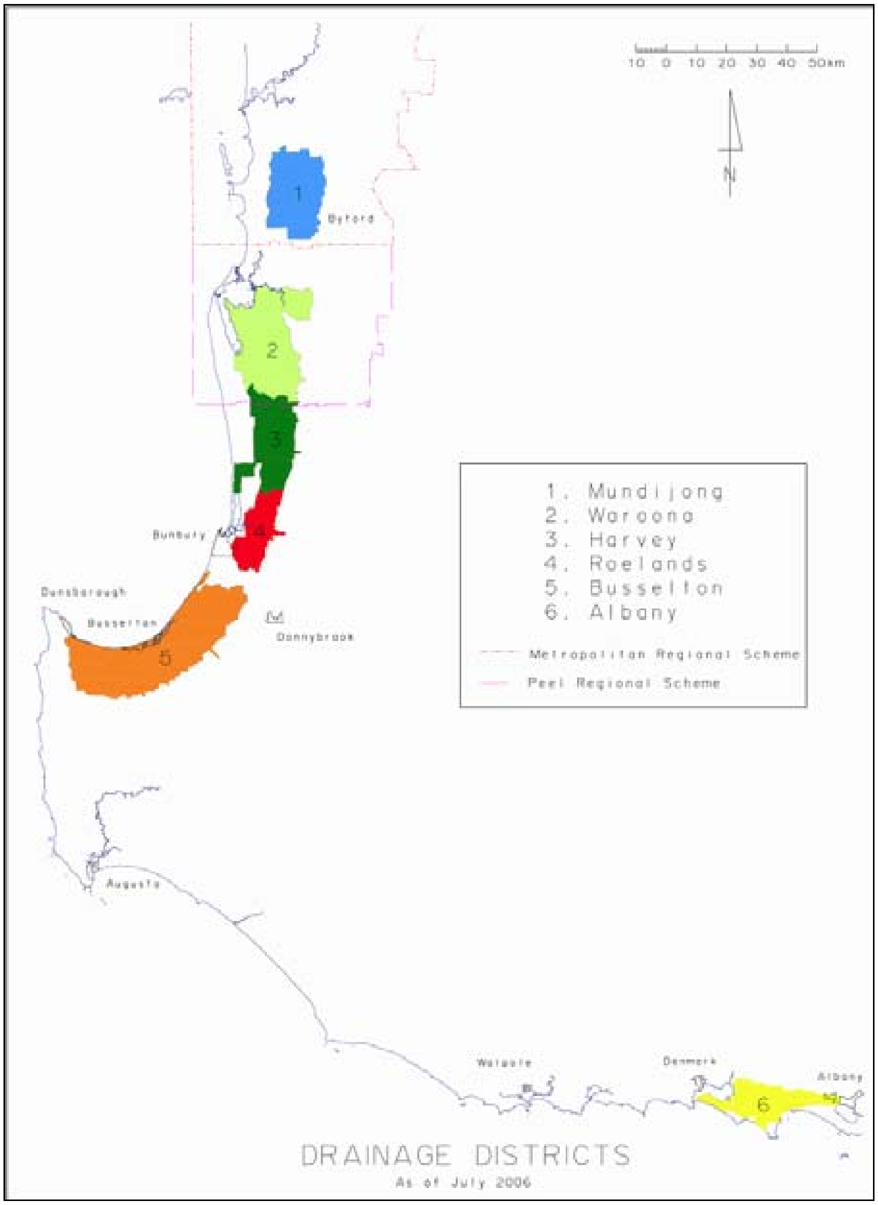


Figure 6-2 Coastal Drainage Districts in WA (Water Corporation)

The six Drainage Districts comprise of 321,324 ha area (English, 1994) and contain 2,510 km of Water Corporation maintained drains, rivers and creeks in the drainage network. The Busselton district has 530 km of drains and covers 103,571 ha area. The Mundijong, Waroona and a large part of the Harvey drainage districts all drain into the Peel-Harvey Estuarine System. There are at least 1,014 km of waterways in the three Gazetted Drainage Districts (English & Doubikin, 1994). There were also 337 public road bridges and 721 public road box and pipe culverts for which the Water Authority was regarded as responsible (English, 1995). Drainage was also being constructed on coastal plains and rural areas outside of the drainage districts, notably in the Scott Coastal Plain.

6.1.7 Peel-Harvey Catchment

Peel-Harvey Catchment has two soil types, the Pinjarra Plain of low permeability and Bassendean Sandplain with a high water table. Drainage of the Pinjarra Plain has often meant creating an artificial channel to continue natural waterways as they flow off the Ridge Hill Shelf. Many drains within the Pinjarra Plain often have a bed of compacted gravel or coffee rock. Where this compacted layer has been removed, drains have often eroded or cut-back upstream. The Bassendean Sands have a very low Phosphorus Retention Index (PRI) of 5 compared with PRI of over 100 with most clays. Drains constructed within the Bassendean Sandplain often have very unstable banks and may be cut at a depth of 3-4 metres through low relief dunes to remove water from localised flats. Flow in these drains is often very slow due to the low grade across the Bassendean landform and sand-build-up in the drain bed.

The coastal plain's drainage system contains flowing water for about 3 to 4 months of the year. In winter, especially after a storm-event, the main drains carry a huge volume of water with nutrients and sediments and flow into estuaries. In the dry part of the year, most of the drains and other waterways are often dry, vegetated and grazed (Del Marco, 2007).

Different types of drains in the area are shown in Plate 6-1, Plate 6-2, Plate 6-3 and Plate 6-4.

Plate 6-1 Feeder drains, paddock drains, such as this example in Coolup (Adapted from Del Marco, 2007)

Plate 6-2 Medium sized artificial waterways (second and third order waterways) such as the Punrak Drain at Serpentine (Adapted from Del Marco, 2007)

Plate 6-3 Main drains; Large artificial waterways such as the Birrega Main Drain at Mundijong (Adapted from Del Marco, 2007)

Plate 6-4 Roadside table drain discharge into the Peel Main Drain, Baldivis (Adapted from Del Marco, 2007)

Del Marco (2007) has provided an inventory of waterway channels and assets associated with them in Peel-Harvey Catchment. The Mundijong, Waroona and a large part of the Harvey Drainage Districts all drain into the Peel-Harvey Estuarine

System. There are at least 1,014 km of waterways in the three Gazetted Drainage Districts (English & Doubikin, 1994). The gazetted system contains a wide range of large and medium scale waterways, including 120 km of 'managed creeks and rivers' (Table 6-1). In addition to the waterway channels, the gazetted drainage system includes road and rail bridges, occupational crossings, cattle stops, drop structures, compensating pipes, outlets from properties, erosion protection structures, and access tracks. In all, there were over 2,000 physical assets managed by the Water Authority in 1994. The last publicly-available inventory of these structures was provided in 1994 by the Water Authority (English, 1994) (English & Doubikin, 1994) and is summarised in Table 6-2.

The Rights in Water and Irrigation Act 1914 was amended in 1984 to give the Water Authority the power to prohibit drainage works that were likely to affect the water in a watercourse, wetland or underground water source. However, this power has rarely, if ever, been used in relation to rural drainage.

The Soil and Land Conservation Regulations 1992 provided the Commissioner of Soil and Land Conservation with the responsibility for assessing and approving drainage. This applied predominately to drainage that would drain subsurface water with the aim of controlling salinity and did not apply to the majority of drainage on the coastal plains. However, under Regulation 6 it did include any drainage in the Peel–Harvey Catchment and therefore did have an impact on the Mundijong, Waroona and Harvey Drainage Districts (URS, 2004).

Table 6-1 Estimated length of drain, managed rivers and creeks as declared (gazetted) drains in Local Governments within the Peel-Harvey Catchment (km) (Adapted from Del Marco, 2007).

Local Government	**Main drains** *(Km)*	**Branch drains** *(Km)*	**Managed rivers** *(Km)*	**Managed creeks** *(Km)*	***Total*** *(Km)*
Rockingham	55.4	27.5			*82.9*
Serpentine-Jarrahdale	44.3	180.	17.1	12.6	*254*
Murray	55.4	213.3	2.4	26.7	*297.8*
Waroona	32.9	107.3	22.9	13.5	*176.6*
Harvey	48.8	127.6	26.9	0	*203.3*
TOTAL	***236.8***	***655.7***	***69.3***	***52.8***	***1014.6***

Table 6-2 Physical assets of the three Gazetted Drainage Districts (1991/92 analysis) (Adapted from Del Marco, 2007).

Structure	**Mundijong DD**	**Waroona DD**	**Harvey DD**	***Total***
Timber bridges	45	46	60	*151*
Concrete bridges	58	127	210	*395*
Steel bridges	1	0	0	*1*
Bridges (pipes or box culverts)	147	380	215	*742*
Concrete structures	24	1	37	*62*
Pipe outlets (floodgates)	28	55	18	*101*
Timber checks	2	0	0	*2*
Cattle stops	230	181	165	*576*
TOTAL	***535***	***790***	***705***	***2030***

Each of these systems drains what was once either waterlogged or seasonally or permanently inundated land (Hill, *et al*., 1996). Once drained these soils, complemented in some case with irrigation, constitute some of the most productive lands in WA supplying a wide range of agricultural produce including milk, meat, vegetables and orchard products. The drainage system takes excess water from these low-lying areas to the coast either through adjacent estuarine or ocean outlets. To stimulate agricultural development, existing watercourses have been improved and extensive drainage networks created by the Government. Beginning some 30 km south of Perth the drainage schemes extend south for 200 km, plus an area immediately to the west of Albany servicing an area of about 200,000 ha.

The flow rate in drains in a drainage district is different because of different hydraulic designs. Most drains are steep sided due to lower construction costs, width of drainage and road reserves and the commercial value of the land in the district. The drains range from 1 m to 10 m deep and 2 m to 50 m wide with a levee bank or soil spoil heap on one or (rarely) both sides and an access track immediately adjacent to the drain on one or both sides. The levee banks and spoil heaps are deliberately placed beside the drainage channel to ensure disposal of water from private land into the drains is only possible through specified and controlled outlets. In most cases, the access track has to be wide enough for mechanical maintenance of the drain.

Therefore, the access track is usually 4-6 m wide depending upon the size of the drain and the size of the machinery required maintaining the drain (KABAY, 2002).

Operation and maintenance of the majority of drains within these districts is the responsibility of the Water Corporation. Other drains within the districts are the responsibility of local authorities, landholders, Main Roads or other agency. Due to the impact on downstream water bodies, water quality as well as quantity is now an important consideration in the design and management of drainage systems. There are varieties of best management practices that can be adopted to improve water quality and reduce flow rates:

• Point source techniques: Soils testing, fertilizer management, effluent management plans and surface water control (maximise infiltration and reuse).

• Diffuse source techniques: Fencing of waterways, vegetation buffer zone and paddock level retardation basins/artificial wetlands (allowing nutrient stripping, sediment deposition and/or reuse).

• In-stream techniques: Naturalisation, riffles, silt traps/trash racks and on/off line storage (allowing nutrient stripping, sediment deposition and/or reuse).

Retrofitting existing systems to install diffuse source and in-stream best management practices, particularly in main arterial channels, will inevitably create problems and be costly. A key finding from a major project in the Peel–Harvey Region was that implementing best management practice techniques (that require significant earthworks) in arterial drainage channels is unlikely to provide cost-effective solutions to improving water quality (Del Marco, 2007).

The rural main drainage system that has been created within the drainage districts deteriorates over time and requires regular maintenance. This deterioration includes:

1. Production of excessive growth of critical weed species within the drain that can block the drain and decrease their water carrying capacity. These need to be removed either by control with herbicide spraying or mechanical removal.

2. Siltation of the drain through soil erosion of adjacent land and the formation of sand bars within the drain which redirect water flow to the sides of the drain causing undercutting of the banks and further drain erosion. The extra soil load and its associated vegetation within the drain decrease its capacity and can therefore cause flooding. The excess soil/vegetation is mechanically removed and deposited on the edge of the drain, usually on the access track if this does not impede its use.

3. Deterioration of assets such as bridges, culverts and connecting pipes.

Possible environmental remedial works on drains on private property or in drainage reserves abutting private property.

• Creation of parallel linear filters to improve the quality of water entering the drain from farms

• Construction of stilling sumps at the end of feeder drains

• Fencing to exclude stock

• Revegetation of drainage banks for commercial (cut flower, fodder, woodchips shelterbelts etc) or conservation (wildlife corridors) values.

• The majority of drainage networks are established, predominately within the declared Drainage Districts

• The management of the drainage networks has evolved over time, and there have been numerous attempts to streamline ownerships and maintenance responsibilities

The Water Corporation is responsible for the majority of water conveyance structures in Drainage Districts and local government manages some smaller areas. There are other key stakeholders who are responsible for or have a vested interest in the design of drainage for a variety of reasons (e.g. Economic Regulation Authority, landholders, Industry, Main Roads, WestNet Rail, local government and DoW).

Therefore, best management practices must include maintenance regimes and procedures. Alternative maintenance practices include banded drain clearing, channel broadening and/or spot clearing/silt traps (Del Marco, 2007).

Changes in agricultural practices need to be considered to ensure that the drainage networks are not too efficient at removing surface water. The Water Corporation maintains the existing system under the three-day rule (Water Corporation, 2006). However, due to the use of pasture species that are more tolerant to waterlogging, the allowable period of inundation could be raised to six days (Davies and Muir, 1994). In cases where drainage channels have become deep enough the system may be lowering the local groundwater, which can have adverse impacts on adjacent crop and pasture productivity. This was supported when drainage water was retained within the Mealup Drain by the installation of unauthorised locks (Bradby, 1997).

6.1.8 Climate Impact

McFarlane (2005) reported that since the mid-1970s the South West of Western Australia has probably experienced one of the most profound impacts of climate change of anywhere in the world. After 1975, the May to July rainfall for the South West abruptly decreased by about 15%. As well as a reduced average rainfall, the absence of very wet years has resulted in greatly reduced runoff and recharge. The May to July rainfall for the South West abruptly decreased by about 15% after 1975 (IOCI, 2004). The rainfall data analysis of all cities in the south-west of Western Australia indicate that annual rainfall has been decreasing since 1969 for some cities in the region and rainfall is decreasing in some cities since 1975. The winter season rainfall shows a downward trend and summer season rainfall shows an upward trend linked to an increase in the frequency of summer storm events in the south-west, in the Wheatbelt and in the east of Western Australia (Chapter 5).

Climate has a significant impact on natural resource processes, including:

Waterlogging

Heavy rainfall increases waterlogging, adversely impacting crop yield. McFarlane and Williamson (2002) have identified three types of waterlogging. These are associated with perched aquifers in duplex soils, inundation of terraces and valleys, and saturation in surface soil due to the hydraulic pressure being above ground level in aquifers at the base of the regolith of highly weathered granites and gneisses or within channels in broad valley sediments. Waterlogging has reduced the potential yield by 30–80% for many crops and pastures in the areas with mean annual rainfall of more than 400 mm.

Effective water management can reduce productivity losses caused by excess water in the landscape. Engineering interventions such as deep drains and groundwater pumping improve the outflow of water from both the saturated and unsaturated soil zones and reduce periodic seasonal events such as waterlogging and inundation.

Erosion

Drought causes soil erosion. Drought reduces grass cover, which along with grazing, causes soil erosion. Practices to manage grazing pressure and retain pasture cover include crash graze and spell, minimise impact on waterways and trap sediment leaving the paddock.

Soil loss on farm is irreversible and impacts that occur off-farm which will continue for many generations. Catchment management in terms of implementing improved practice are essential including soil management targets.

Soil Acidity

Rainfall could increase soil acidity. Soil pH values in some agricultural regions tend to be lower as annual rainfall increased, therefore lower near the coast than further inland. This broad observation in Victoria (Australian Agriculture Assessment, 2001), particularly noticeable in transects inland from the eastern and southern coastlines, may be associated with soils in higher rainfall areas being naturally more acidic or, as in most cases, associated with the rate of induced acidification being more rapid in these higher rainfall environments.

An integrated approach to fertiliser management will be needed to assess nutrient requirements and soil acidity hazard. Fertiliser management is important in the higher rainfall regions - from a soil acidity perspective and also recognising leakage of nutrients to groundwater and transport of nutrients by overland flow to waterways (Australian Agriculture Assessment, 2001).

Other management options that can be considered include stock management and the use of perennials in the pasture management cycle.

Nutrient Transport

Rainfall increases nutrient transport. The Australian Agriculture Assessment, 2001 reported that highly positive nutrient balances can be recorded in higher rainfall regions where dairy and horticultural industries often co-exist due to the regular use of fertilisers and generally higher soil fertility status. This highlights the importance of nutrient balance and fertiliser management to vegetation.

6.1.9 Water Use

Dry spells increase irrigation requirements and water usage. Productivity of agriculture is generally greater in more reliable rainfall areas (Australian Agriculture Assessment, 2001). Dry spells increase irrigation requirements, resulting in increased water usage and less efficiency.

Water use by vegetation i.e. trees, bushes, grasses, annual crops and pastures, is the lowest when rainfall is the highest. Low water use means that rainfall can infiltrate quickly past the root zone to recharge the watertable. By the time the annual plants are into maximum water use between September to November, most recharge has already occurred.

In some regions, more diversified and intense systems of cropping with appropriate crop management will need to be adopted to minimise future risks of deep soil drainage of water and nitrate leaching. In others, the replacement of annual pastures with perennials maybe a more viable option to address acidity, water use efficiency and salinity hazard issues (Ridley *et al*., 2001).

6.1.10 Monitoring and Evaluations

The combination of soil salinity and waterlogging results in pasture yield losses. Currently it is estimated that on the Coastal Plain 10% (5 400 ha) of non irrigated and 22% (7,700 ha) of irrigated agricultural land is salt affected and suffer yield reductions more than 25% due to salinity (Ecotones & Associates, 2005). These areas are predicted to increase and may reach a maximum of to 43% and 80% respectively by 2020 if current trends continue (Yesertener, 2005).

Estuaries in the South West are particularly vulnerable to nutrient enrichment, as they have evolved under naturally low nutrient conditions and many catchments now support intensive land uses. Nutrient levels vary significantly in South West estuaries (Figure 6-3 and Figure 6-4) and are related to estuary size, rate of flushing and catchment land uses. Estuarine nutrient levels are generally stable over time, requiring several decades of monitoring to detect change. The Peel-Harvey estuarine system is an exception, with construction of the Dawesville Channel making this estuary more marine-like and dramatically lowering nutrient levels and algal activity. While most nutrient-enriched estuaries experience elevated algal blooms, some estuaries (such as the Oldfield and Moore) have naturally dark, tea-coloured water that is less favourable for algal growth. Estuaries in the rangelands are not well monitored for nutrients or algal activity (http://www.environment.gov.au).

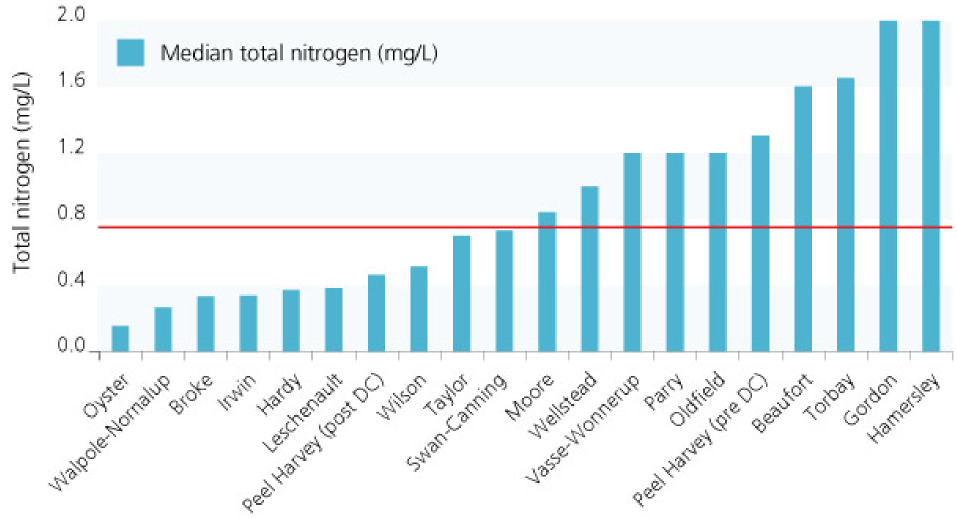


Figure 6-3 Median Total Nitrogen in South West Estuaries
(http://www.environment.gov.au)

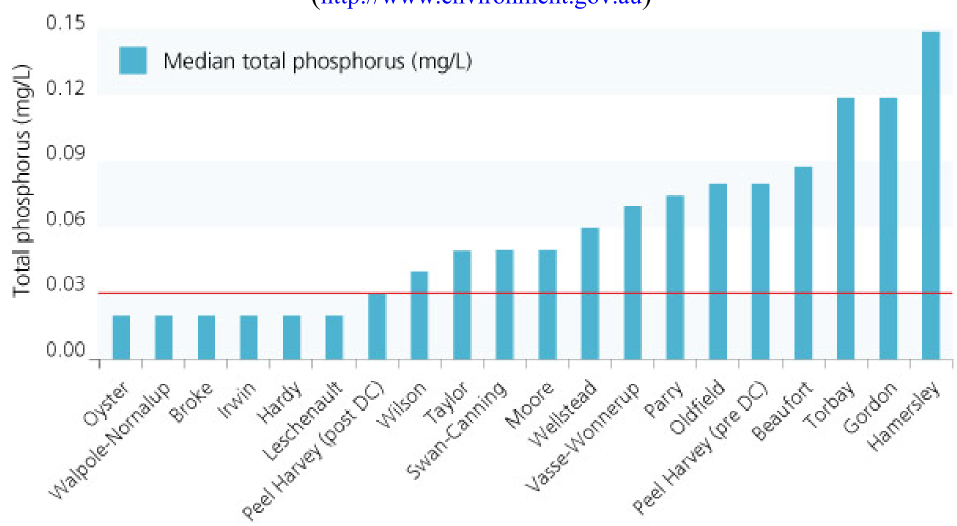


Figure 6-4 Median Total Phosphorus in South West Estuaries
(http://www.environment.gov.au)

6.1.11 Landuse Impacts

The Coastal Plain (800-1,000 mm per year rainfall) lies between the Darling Fault in the east and the coast to the west and extends from Perth to Busselton. Land use is mainly beef production and dairying on flood irrigated and dryland annual pastures. Population density and land values are high. The plain is of low relief, formed of sediments deposited from rivers flowing from the Darling Ranges and marine processes which have deposited sands and swamp sediments. Heavy clay soils of the Guilford Formation comprise most of the superficial soils. The sandier, brackish

Yoganup formation, which outcrops at the base of the Darling Scarp, separates the Guilford from the underlying Leederville Formation. The Leederville Formation contains large supplies of fresh groundwater and is recharged from the Yoganup formation in the east. The area is extensively drained, however because of the low relief waterlogging is a major problem in winter.

6.1.12 Point and Diffused Pollution Sources

Agricultural point sources include intensive horticulture, animal feedlots, poultry farming and dairy sheds. In WA the large majority of point sources are known and where they are located but how they contribute their loads to the environment are not well known. Point sources on the Swan coastal plain include landfill sites, contaminated sites, commercial and industrial operations, and intensive livestock areas. Very high ammonia and nitrate concentrations have been recorded near intensive poultry and pig farming localities and the disposal of their associated liquid wastes. Septic tanks in urban areas are important sources of concentrated N that is mobilised primarily by groundwater (Gerritse *et al.*, 1990).

On the Peel Harvey catchment, 44 sites have license conditions established by the EPA (A review of Environmental Protection Regulations to protect the Peel Harvey system). These sites are listed in the DEP's PPS database (Pollutant Point Source database). Each site has a license based on the maximum export rate, which has been evaluated at 1kg TP $ha^{-1}year^{-1}$ for an average year.

The main agricultural point source of nutrients is dairy sheds. Dairy farming is a major industry in the Geographe Bay region with approximately 46 dairy farms spread throughout the catchment. The nutrient contribution from these 46 dairy sheds is approximately 30.6 tonnes of TN and 5.3 tonnes of TP a year (Kelsey, 2004).

Diffuse sources of N largely originate from rural practices including fertilised arable lands, pasture, orchards and intensive horticulture practices where fertiliser application is excessive and groundwater levels are high (Gerritse, 1992; Lantzke, 1999). In urban areas, appreciable quantities of fertilisers are applied to parks, gardens and sports grounds. It has been estimated that fertilisers applied to urban gardens account for approximately 10% of total nutrient inputs to the Swan–Canning Estuary (SCCP, 1999).

The dominant pathway for nitrate leaching from Darling Plateau catchments is surface run-off and sub-surface storm flow (Turner and Macpherson, 1990). Most of the nitrate is leached during the first major rainstorms of winter (sometimes more than 20 mg L^{-1} nitrate), after which nitrate concentration rapidly decreases. Nitrate concentrations are typically less than 1.0 mg L^{-1} in the shallow perched groundwater and less than 0.1 mg L^{-1} in deep groundwater.

The low concentrations suggest groundwater is not a major pathway for N to tributaries from the Darling Plateau (Turner *et al*., 1991). The Darling Scarp has more similar sediment characteristics to inland Wheatbelt areas than the coastal plain and thus N transport and nutrient levels described there may be indicative of inland conditions.

Nitrogen and P are the nutrients most frequently identified as being in limiting supply in aquatic systems. On average, phytoplankton growth uses N and P in the mole ratio of 16:1 or 7:1 by weight. This ratio can be used to identify which of these nutrients is in limiting supply from analyses of nutrient concentrations, provided that the total supply of available nutrient is measured and that phytoplankton growth reduces one of the nutrients to limiting levels.

The bulk of P carried by streams in inland Australia is thought to be derived from P sourced from stream bank collapse and gully erosion of readily dispersible soils (Davis *et al*., 1998b; Wallbrink *et al*., 2003). In Murray Darling Basin river systems, it is likely that most of the P on river sediments is naturally derived from subsoils (Davis *et al*., 1998b). In contrast, nutrient exports from intensively farmed land in tropical Australian catchments have a high percentage in a soluble form, often attributable to fertiliser sources (Davis and Koop, 2001; Hunter and Armour, 2001).

In Australia, the effect of N on water quality has generally received less attention than P. In many freshwater and estuarine systems, N rather than P, can be the nutrient that limits weed or algal growth (Ford and Bormans, 2000; Hart and Grace 2000). A low N:P ratio is associated with increased risk of dominance of cyanobacteria, affecting water quality (Ford and Bormans, 2000). Much of the N research in Australia has focused on estuarine environments rather than freshwater (Hart and Grace, 2000). Recent research suggests that N plays an important role, for example, in riparian zones (Rassam *et al*., 2003), irrigation (Mundy *et al*., 2003) and surface and groundwater (Davis and Koop, 2001; Hunter, 2000).

6.1.13 Nutrients

Algal blooms and associated events (such as fish kills, unpleasant odours, mussel contamination and closure to recreation) regularly affect many rivers and estuaries in WA.

The Blackwood River, with headwaters over 300 km to the north-east of its mouth, is the longest of the rivers and flows through the south-west of Western Australia. The major tributaries of the Blackwood Rivers are Arthur, Coblinine, Beaufort and Balgarup Rivers. Average annual salinity levels in the rivers range from 3,000 to 8,000 mg L^{-1}.

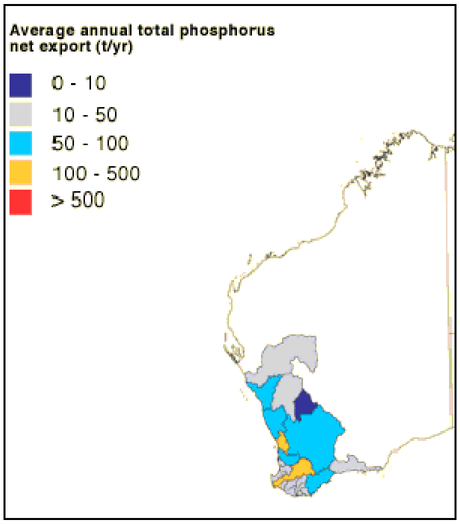
The average net total phosphorus export by river network in Western Australia is given in Figure 6-5. The highest average net total phosphorus export by the Blackwood River with a catchment area of 22,550 km^2 and mean annual basin flow of 1,060 million m^3 is 100-500 t $year^{-1}$. The dominant sources of phosphorus (over 50%) are gully and river bank erosion, and dissolved phosphorus in run-off in coastal Western Australia. The highest average net total nitrogen export by the Blackwood River is 1,000-5,000 t $year^{-1}$.

Peel-Harvey Estuary includes Murray, Serpentine and Harvey River catchments and has 12 070 km^2 catchment area and a mean annual basin flow of 1 050 million m^3. Peel Harvey has an average annual total phosphorus net export of 50-100 t $year^{-1}$ and average annual total nitrogen net export is 1,000-5,000 t $year^{-1.}$

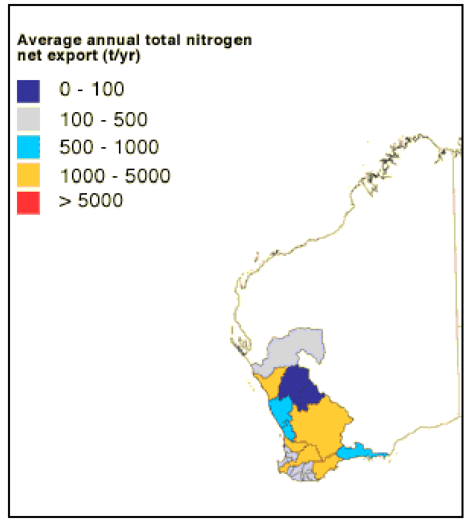
Leschenault Inlet includes Collie, Brunswick, and Oreston River catchments and has 4 780 km^2 catchment area and a mean annual basin flow of 560 million m^3. Leschenault has an average annual total phosphorus net export of 10-50 t $year^{-1}$ and average annual total nitrogen net export is 100-500 t $year^{-1}$.

Geographe and Margaret includes Capel, Vasse and Margaret Rivers in the north of the Blackwood River and Donnelly, Warren, Shannon, Frankland, Kent and Denmark Rivers in the south of the Blackwood River have the same phosphorus and nitrogen export as that of Leschenault Inlet.

Dissolved nitrogen in run-off makes up a greater proportion of the total load than dissolved phosphorus. Total nitrogen loads come mainly from dissolved nitrogen loads in run-off; and over 60% of the total load occurs as dissolved run-off in coastal Western Australia is shown in Figure 6-5.



Total Phosphorus



Total Nitrogen

Figure 6-5 Average Net Nutrient Export by River Network
(http://www.anra.gov.au/topics/water/pubs/national/agriculture_nutrient_loads.html)

6.1.14 Dissolved Solids

The prospect of increasing volumes of effluent produced by deep drains has increased concerns about the acidic, trace element rich waters that can be produced by such drainage systems and the impacts of these on receiving environments (Dogramaci and Degens, 2003). Initial investigations of some major drainage schemes have found that these can discharge waters of pH 2-3 with a salinity of 30,000 to 50,000 mg L^{-1} at 5-10 ML per day (Ali *et al.*, 2004b). There are no reports of investigations to characterise the geochemical risks associated with these drainage waters, though limited studies indicate that the waters can contain elevated Al, Mn, Co, Ni and Pb (Ali *et al.*, 2004b; Tapley *et al.*, 2004). Shallow acidic groundwater likely to be intercepted by the drains can contain significant concentrations of Al, Cu, Fe Mn, Pb and Si (Mann, 1983; Lee and Gilkes, 2005).

6.1.15 Peel Harvey Catchment

The Peel-Harvey Estuarine System (PHES) is located 75 km south of Perth in south Western Australia. The system consists of two interconnected shallow lagoons, the Peel Inlet and the Harvey Estuary, into which the Murray, Serpentine and Harvey Rivers discharge. Prior to construction of the Dawesville Channel in 1994 the only connection between the PHES and the ocean was the Mandurah Channel, a narrow 5 km long channel connecting the northern end of the Peel Inlet to the Indian Ocean.

Land use in the Peel-Harvey region is highly diversified. Residential, commercial and agricultural practices flank the estuaries, while agriculture is the dominant land use activity on the coastal plain region. Stock grazing and pasture development are the most common agricultural activities, although horticulture and industry are also present. A small portion of the region is irrigated and has a developed network of drains. Approximately 75% of the coastal plain is cleared of native vegetation. The land east of the Darling Scarp remains largely forested with native Eucalyptus marginata and several rivers in the region have been dammed. The land to the east of the plateau is largely cleared for stock grazing, pasture development and cereal crops.

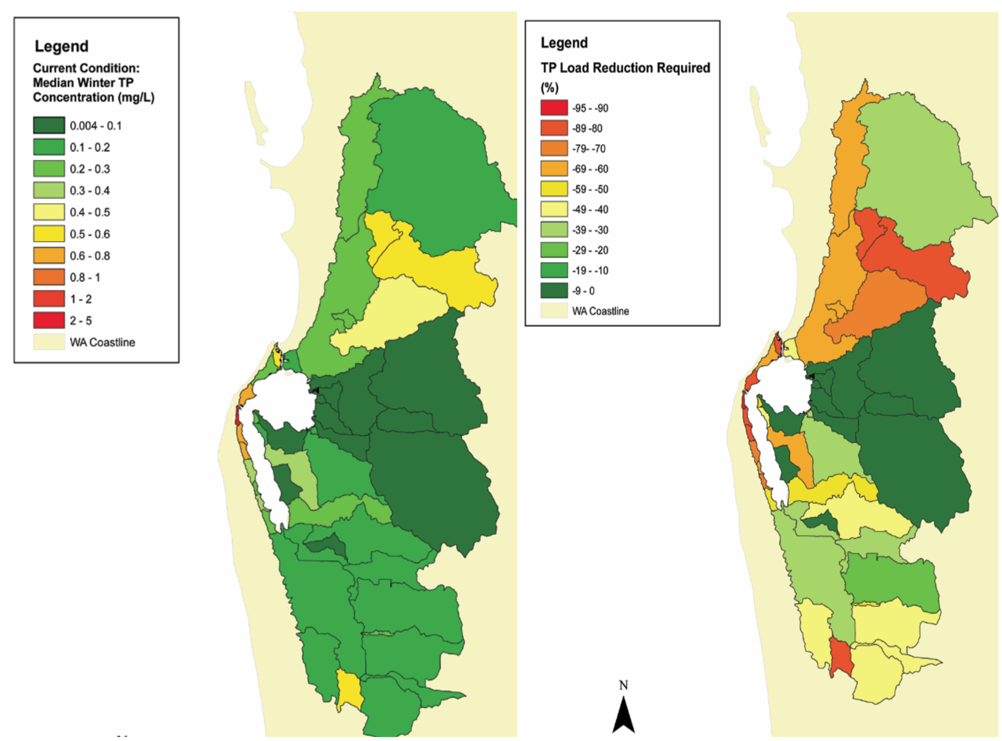
The Peel-Harvey catchment can be divided into three broad regions: the coastal plain, the forest region and the agricultural region. The coastal plain is bound to the east by the Darling Scarp and to the west by the ocean, and has largely been cleared of remnant vegetation. The forested region flanks the western part of the Darling Range and the agricultural region to the east. The catchment receives around 90 per cent of the annual rainfall between April and October. Average annual rainfall in the coastal plain region of the catchment is approximately from 700 to 800 mm, while in the areas adjacent to the scarp this is as high as 1,000 mm. Of this rainfall, approximately 50% of the total annual volume enters the estuary between July and August, with more than 66% entering between June and October. Most streams experience little or no flow between December and through to April, comprising mostly groundwater input at this time.

Tributary inflows to the PHES have been susceptible to nuisance phytoplankton blooms over an extended period. Phytoplankton blooms in these reaches of the PHES can be difficult to control and manage, and can be attributed at least in part to the continuous export of nutrients from the catchments of the Serpentine, Murray and Harvey rivers.

Run-off from the total catchment area of 11,378 km^2 enters the PHES via three rivers and 15 agricultural drains. The rivers are the Murray, Serpentine and Harvey. Approximately 95% of the run-off occurs between May and October. The Harvey catchment has been extensively cleared and drained for agriculture. Irrigated pastures in the south-east portion support a major dairy industry and some intensive horticulture, while clover-based pastures in the central and western portions support beef cattle, sheep and hay production. The Murray catchment contains mostly wheat and sheep farms. The Serpentine catchment has undergone the least clearing for agriculture, but there are some productive horticulture and grazing areas and hobby farms. Waters from the largely unmodified forested catchment of the Serpentine have been diverted for potable water supplies.

6.1.16 Water Quality Targets

The water quality standard is set in Peel Harvey so that water quality at the draining point (outlet) of each catchment meets a median winter concentration value of 0.1 mg L^{-1} for TP. Most of the fertliser load is transported in the winter season in the 17 catchments in Peel-Harvey. The load and concentrations are expressed in terms of median winter load and concentration calculated over the period June to October. EPA (2007) has modelled the predictions of TP load and concentration as they are now and how they need to change in order to meet the load and concentration targets (Figure 6-6). Excessive levels of N and P are the cause of algal blooms and aquatic weed growth in surface waters.



a) Current Concentration b) Target Loads

Figure 6-6 Total Phosphorus loads (TP) in Peel Harvey (EPA, 2007)

6.1.17 Current Conditions

On the Peel Harvey catchment, there are 22 sites licensed by the National Pollutant Inventory (NPI) for emissions to land and/or water. Of these, six sites have TP emissions which are greater that the reporting threshold for Phosphorus (of 3 tonnes per annum) and are thus required reporting their emissions of TP to the NPI.

Data collected from sampling sites at the bottom of the Murray and Harvey rivers showed low nutrient status for both nitrogen and phosphorus. However, the status of nitrogen and phosphorus in waters at sites along much of the Serpentine River were found to be high to extreme.

6.1.18 Monitoring & Evaluation Projects

- Peel-Harvey Water Quality Recovery Programme, funded by the Australian and Western Australian Governments for the South West Catchments Council Regional NRM Investment Plan 2006-08.
- Coastal Catchments Initiative (CCI) Projects, funded by the Australian Government, seek to deliver significant reductions in the discharge of pollutants to agreed hotspots, where those hotspots have been identified through agreement with the relevant jurisdictions. This initiative has two stages:

1) Agree on the coastal hotspots and preparation of water quality improvement plans.

2) Invest in water quality projects most likely to deliver cost-effective water quality improvements (http://www.bae.ncsu.edu/programs).

4.3 Geographe Bay Agricultural Nutrient Sources

The Geographe Bay catchment is dominated by agriculture which makes up 63% of the area. Nutrients come from both large point sources and broad scale diffuse sources. Diffuse sources are those which are less intensive land uses and cover a large area; these include cattle and sheep grazing. Point sources are intensive land uses which produce a large amount of nutrients using a small area, for example, dairy sheds and beef feedlots.

The main diffuse sources of nutrients in the catchment are cattle grazing, sheep grazing, forestry, horticulture and viticulture. The largest being cattle grazing, which includes beef and dairy cows. Cattle grazing in the Geographe catchment has an annual nutrient export of approximately 268 tonnes of TN and 131 tonnes of TP each year (Kelsey, 2004). Grazing is a non-intensive land use but has a large nutrient contribution as it occupies approximately 36% of the catchment (Kelsey, 2004; Deeley, 2002).

Recent monitoring of Geographe Bay indicates that water quality has worsened significantly over the last decade due to the increased pressure from agricultural and urban land uses (SKM, 2003). Of particular importance is the Vasse-Wonnerup Estuary, which despite being listed as a wetland of ecological importance under the Ramsar convention in 1990, is recorded as having the greatest input of nutrients per square metre of catchment of all estuaries in Western Australia (McAlpine *et al.*, 1989).

The main agricultural point source of nutrients is dairy sheds. Dairy farming is a major industry in the Geographe Bay region with approximately 46 dairy farms spread throughout the catchment. The nutrient contribution from these 46 dairy sheds is approximately 30.6 tonnes of TN and 5.3 tonnes of TP a year (Kelsey, 2004). TN and TP export from the Vasse-Wonnerup catchment is given in Figure 6-7 and Figure 6-8, respectively.

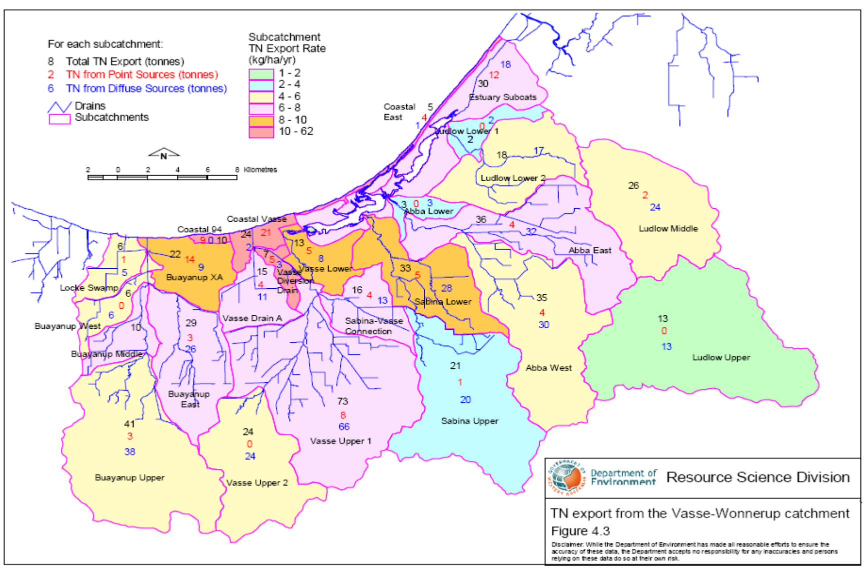


Figure 6-7 TN Export from the Vasse-Wonnerup Catchment (Department of Environment, 2004)

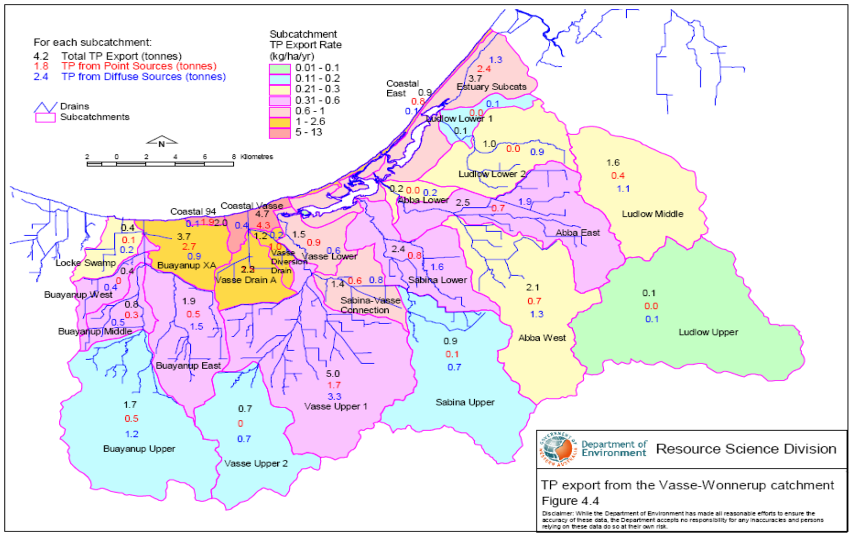


Figure 6-8 TP Export from the Vasse-Wannerup Catchment (Department of Environment, 2004)

6.1.19 Monitoring & Evaluation Projects

The Geographe Bay catchment Council has several projects underway that targeted priority issues of effluent and nutrient management and water use efficiency.

Some of these projects include:

- River Action Plans
- Lower Vasse River Cleanup Program
- Ribbons of Blue
- Biodiversity Hotspot Project
- Dairy Catch
- Nutrient Smart
- Geographe Weed Action Group
- Geographe Catchment Companion

The River Action Plans assist landholders to protect and enhance of riparian vegetation and to reduce nutrients entering waterways and downstream wetlands and Geographe Bay.

They provide advice and funding for:

- Fencing of waterways;
- Construction of livestock crossings and erosion control measures;
- Weed control along waterways;

- Revegetating waterways; and
- Other benefits of restoring your waterway.

The Dairy Catch provided funding support for dairy farmers to develop and implement best practice effluent plans to measure costs and benefits of best practice.

The Nutrient Smart Project will improve knowledge and activities associated with fertiliser management on working farms. It aims to maximise farm productivity from appropriate fertiliser application to and reduce wastage and nutrient export to the catchment.

The Streamlining project was funded over a three-year period to ensure progress towards the sustainable management, rehabilitation and conservation of rivers.

6.1.20 Leschenault Catchment

The Leschenault estuarine system is located to the north of Bunbury and 180 km south of Perth (Figure 6-9). The Leschenault Estuary is a shallow, elongated water body, lying roughly northsouth and separated from the Indian Ocean by a sand dune peninsula. The estuary is about 13.5 km long, up to 2.5 km wide and has a surface area of approximately 25 km^2. The Estuary is connected to the Indian Ocean via a narrow, artificial channel in the south ('The Cut'). The Leschenault water catchment has an area of 1,981 km^2, encompassing the Wellesley, Brunswick, (lower) Collie, Ferguson and Preston River sub-catchments. The Collie and Preston Rivers discharge directly into the estuary at its southern end with runoff from the catchment discharging into the ocean via "the Cut" through the peninsula.

Leschenault Estuary and Inlet have changed considerably as a consequence of the introduction of 'the Cut' in the 1950s and the subsequent development of the Bunbury Inner Harbour. The Leschenault waterways are relatively healthy except the lower river systems exhibit increasing pressure, such as high nutrient levels, algal blooms and occasional fish deaths.

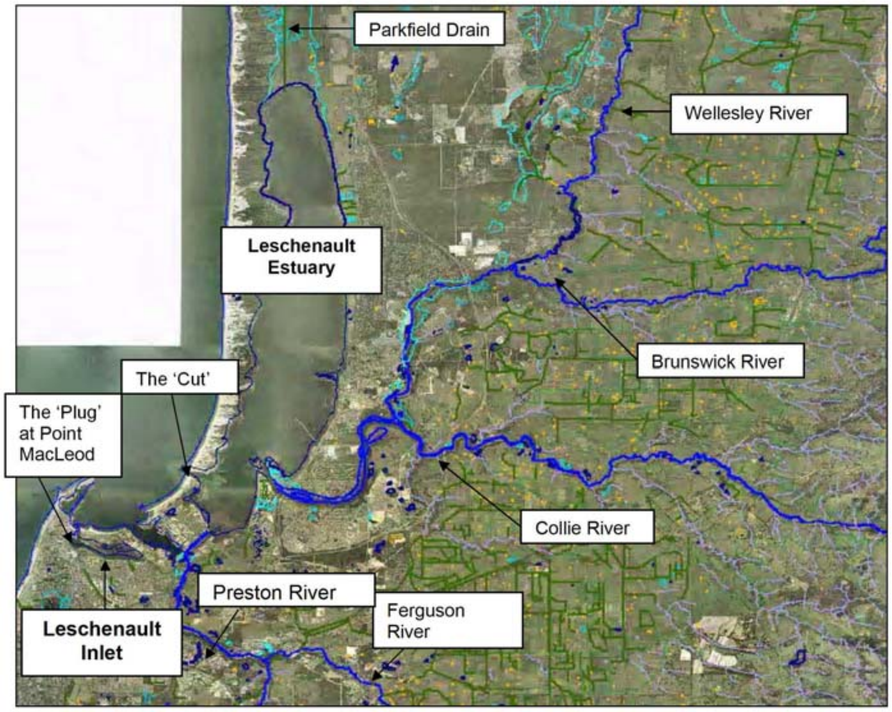


Figure 6-9 Waterways of the Leschenault Catchment using Aerial Photo of 2003, (DoW)

Department of Water has monitored stream flow and water quality at a number of sites in the area. The main indicators used to monitor nutrient enrichment in waterways are total nitrogen (TN) and total phosphorus (TP). Table 6-3 was used for classification of nutrient status for total Nitrogen (TN) and total Phosphorus (TP) at the monitored sites of the Leschenault Estuarine System.

Table 6-3 Classifications used to assess the status of TN and TP concentrations in monitored (estuarine) waterways

TN (mg/L)	**TP (mg/L)**	**Status**
>2.0	>0.2	Very High
1.2-2.0	0.08-0.2	High
0.75-1.2	0.02-0.08	Moderate
<0.75	<0.02	Low

6.1.21 Lower Collie River

Total Nitrogen (TN) and Total Phosphorous (TP) concentrations in lower Collie River were 'Moderate' to 'High' over the summer and autumn periods. TN concentrations in 65% of samples exceeded the recommended ANZECC/ARMCANZ (2000) guideline of 0.75 mg L^{-1} for south west Australian estuaries. TP in 2000 showed a 'High' phosphorous concentration status at nearly 0.1 mg L^{-1} to a 'Moderate' concentration of at 0.06 mg L^{-1} in 2006. The 95% of samples recorded from 2000 to 2006 period exceeded the recommended maximum ANZECC/ARMCANZ value of 0.03 mg L^{-1} with over 10% of all samples classified as exhibiting a 'Very High' TP concentration (Ramsay, 2006).

6.1.22 Lower Brunswick River

During 2000-2006 monitoring period, a 'Moderate' to 'High' TN and a 'High' Total Phosphorous (TP) status was recorded with over 95% of TN and 98% of TP samples recorded exceeding the recommended maximum ANZECC/ARMCANZ (2000) TN value of 0.75 mg L^{-1} and 0.03 mg L^{-1} TP indicating increased risk of problems associated with nutrient enrichment. Irrigation and drainage in the Brunswick River catchment is responsible for high TN and TP load. This high concentration of nutrients in the lower Brunswick River results in algal blooms.

6.1.23 Lower Preston River

The Preston River has a 'Low' TN and 'Moderate' TP status with median concentrations showing no significant trend for TN. While the lower Preston River has a slightly decreasing trend over the last six years in TP median concentrations, approximately 51% of all samples taken between 2000 and 2006 exceeded the ANZECC/ARMCANZ guideline, decreasing to 20% exceedence in the 2006 summer period (Ramsay, 2006). The total rainfall for Bunbury from 2000 to 2006 was below the long-term (1877 to 2007) annual average of 843 mm except in 2005 when annual rainfall of 863 mm was received. The total rainfall for Bunbury in 2006 was only 506 mm. This low concentration of nutrients is may be due to reduced rainfall and runoff events during the recent years.

A summary of monitoring catchment areas with recording periods and TN, TP and TDS concentrations for key sites in the area is given in the Table 6-4.

Table 6-4 Pollutant Loads in Leschenault Catchment

Name	AWRC Name	Average Annual Loads										
		Stream Flow	Rainfall		TP	TP		TSS		TDS		
		(ML)	(mm)	(% rainfall)	(mg/L)	(kg/ha)	(mg/L)	(kg/ha)	(mg/L)	(kg/ha)	(mg/L)	(kg/ha)
VELLESLEY RIVER	PUEGENUP	5,316.60	25.4	2.5	1.7	0.43	0.4	0.1	29	7.37	968.5	246.35
BRUNSWICK RIVER	CROSS FARM	10,682.40	21	2.1	1.6	0.33	0.4	0.08	29.2	6.13	72.2	15.14
BRUNSWICKRIVER	OLIVE HILL	6,183.30	27.4	2.7	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
BRUNSWICK RIVER	BEELA	4,450.20	21.3	2.1	0.6	0.13	0.3	0.06	No Data	No Data	182.7	38.88
COLLIE RIVER	ROSE ROAD	7,652.90	2.6	0.3	0.7	0.02	0.3	0.01	9.5	0.25	747.3	19.63
COLLIE RIVER	SHENTONS ELBOW	11,549.60	4	0.4	No Data	No Data	No Data	No Data	No Data	No Data	436.3	17.63
COLLIE RIVER	MT LENNARD	13,566.60	4.7	0.5	No Data	No Data	No Data	No Data	No Data	No Data	823.8	38.69
BRUNSWICKRIVER	SANDALWOOD	2,140.50	18.4	1.8	0.8	0.15	0.5	0.09	16.8	3.1	45.2	8.32
PRESTON RIVER	PICTON BRIDGE	13,740.40	12.7	1.3	0.8	0.11	0.1	0.01	13.8	1.75	434.5	55.16
PRESTON RIVER TRIB	MANDALAY	134.5	5.6	0.6	No Data	No Data	No Data	No Data	No Data	No Data	581.8	32.73
BEAR DRAIN		184.2	48.5	5.4	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
THOMSON BROOK	NOODPERRY HOMESTEAD	1,223.90	12	1.3	No Data	No Data	No Data	No Data	No Data	No Data	617.9	74.08
PRESTON RIVER	BOYANUP BRIDGE	7,857.50	9.7	1.1	0.8	0.08	0.1	0.01	15.7	1.52	541.1	52.6

6.1.24 Torbay Catchment

The Torbay catchment is located in between cities of Demark and Albany and situated at 26 km west of Albany on the south coast of Western Australia (Figure 6-10). The Torbay Catchment is a fishing, farming, tourism and conservation resource of the south coast of Western Australia. The Torbay Catchment won the prestigious 2006 Thiess National Riverprize award for excellence in river and waterway management.

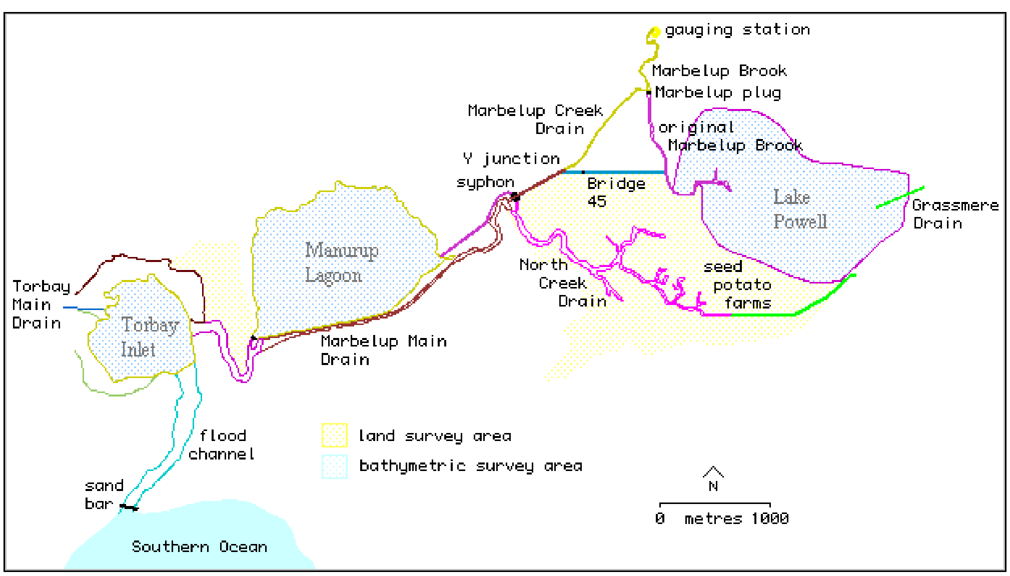


Figure 6-10 Torbay Catchment area (Adeney, 2001)

There are more than 70 km of excavated drains in the Torbay Catchment, excluding feeder drains constructed on individual properties and over 180 km of natural waterways within the catchment (Table 6-5).

Table 6-5 Natural and Excavated Waterways in Torbay

Subcatchment	Drains (km)	Natural Waterways (km)	Swales (km)	Total
Five Mile Creek	3.8	9.7	4.1	17.6
Seven Mile Creek	1.3	22.8	3.5	27.6
Marbellup Brook	0	110	16.3	126.3
Torbay Main Drain	72.5	41.9	47.2	161.6
Total of surveyed subcatchments	77.6	185.4	70	333

About 16% of all waterways in the Torbay catchment are classified as pristine, with the majority of this classification found in the Seven Mile sub-catchment. The largest category of waterway is swales at 21%. Drains comprise 9% of all waterways in the catchment.

Torbay Main Drain has 48% and Marbellup Brook has 38% of waterways in their sub-catchments. The fencing status of the waterways is recorded with the stream order in Table 6-6.

Table 6-6 Fencing of Waterways in Torbay

Sub-catchment	Stream Order	Low Order (1&2)		High Order (3-5)	
		km	%	km	%
Five Mile Creek	Both sides Fenced	0.5	4	0.7	20
	One side Fenced	2.2	15	2.2	63
	No Fence	11.8	81	0.6	17
	Total length (km)	14.6	100%	3.4	100%
Seven Mile Creek	Both sides Fenced	2	8	0	0
	One side Fenced	0.2		1.7	25
	No Fence	21.1	91	5.1	75
	Total length (km)	23.2	100%	6.8	100%
Marbellup Brook	Both sides Fenced	1.8	2	2.1	7
	One side Fenced	10.3	11	4	14
	No Fence	85.4	88	22.6	79
	Total length (km)	97.5	100%	28.7	100%
Torbay Main Drain	Both sides Fenced	11.9	9	15.6	48
	One side Fenced	8.9	7	1.6	5
	No Fence	108.4	84	15.2	47
	Total length (km)	129.2	100%	32.3	100%

The median Total Nitrogen (TP) concentration from 1997 to 2005 was 1.35 mg L^{-1} with annual medians ranging between 1.05 mg L^{-1} (2000) and 2.00 mg L^{-1} (1997). TN concentrations in Five Mile Creek varied between 0.40 mg L^{-1} and 3.80 mg L^{-1}. There is a downward trend of TN and TN concentrations have decreased at a rate of 0.063 mg L^{-1} yr^{-1} over the 1997 to 2005 period.

The median Total Phosphorus concentration was 0.460 mg L^{-1} with annual medians ranging between 0.380 mg L^{-1} (2000) and 0.550 mg L^{-1} (1997) during 1997-2005 monitoring period. TP concentrations in Five Mile Creek varied between 0.010 mg L^{-1} and 4,000 mg L^{-1}. There is no trend for TP concentrations and it remained stable in Five Mile Creek since 1997.

The targets have been set for TN and TP for Torbay catchment for 2020. The median nutrient concentrations (mg L^{-1}) discharged from the sub-catchments should meet the following targets by 2020 (Table 6-7).

Table 6-7 Pollutant Loads in Torbay

Sub Catchment	Current median concentration (TN/TP)	Target median concentration (TN/TP)
Torbay Drain	1.80 / 0.110	1.20 / 0.090
Marbellup Brook	0.68 / 0.077	0.60 / 0.065
Seven Mile Creek	1.00 / 0.130	0.68 / 0.100
Five Mile Creek	1.35 / 0.460	1.00 / to be set
Cuthbert Drain	2.45 / 0.059	2.00 / 0.059
Grasmere Drain	1.40 / 0.200	1.20 / 0.150

6. 2 Best Management Practices Toolbox for Coastal Drainage

A literature review on coastal drainage best management practices (BMPs) in Australia and abroad was done to collect information on BMPs and all information was stored in Excel workbook under headings of ID, BMPs, Categories, Criteria, Description, Criteria, References and Links. More than 420 technical documents were reviewed and numerous websites were visited to collect information about BMPs.

There are 540 IDs in the ‘BMP Toolbox’, it starts with Riparian Buffers and ends at In-Streams Structures (Appendix-6-1). In order to choose a BMP for a special purpose from the ‘BMP Toolbox’ a filter can be used. Select the data command from Excel workbook and press Filter button, drop down menu buttons appear in the ID, BMPs, Categories, Criteria, Description, References and Links headings. In the BMP drop down menu select Text Filters and choose Custom Filters to open the Custom Auto Filter Window. In Custom Auto Filter Window a BMP which contains Silt Trap or Irrigation Management were selected and 82 BMPs out of 540 were filtered as shown in Appendix 6-2. A search for a BMP can be done of any combination of entries in columns of BMPs, categories, criteria and description using Boolean logic. A search for BMPs which contain Nitrogen or Algal Bloom under category resulted in 22 BMPs that are presented in Appendix-6-3.

The coastal drainage system in Western Australia was initially designed and constructed mainly to carry surface water. Initially, the drains were dug as required to maintain the production of wheat, oats, potatoes and citrus crops, which have a very low tolerance to water logging. The channels were then progressively enlarged to accommodate increased flows due to clearing of upstream catchments to expand agricultural areas (English, 1994).

Due to the impact on downstream water bodies, water quality as well as quantity has become an important consideration in the design and management of drainage systems. There are varieties of best management practices (BMPs) that can be adopted to improve water quality and reduce flow rates: they can be divided into three main areas depending on their application:

- Point source techniques: fertilizer management, effluent management plans and surface water control (maximise infiltration and reuse). The main agricultural point source nutrient exporters are dairy sheds. Dairy farming is a major industry in the Geographe Bay region with approximately 46 dairy farms spread throughout the catchment. The nutrient contribution from these 46 dairy sheds is approximately 30.6 tonnes of TN and 5.3 tonnes of TP a year (Kelsey, 2004).
- Diffuse source techniques: fencing of waterways, vegetation buffer zone and paddock level retardation basins/artificial wetlands (allowing nutrient stripping, sediment deposition and/or reuse).
- In-stream techniques: Naturalisation, riffles, silt traps/trash racks and on/off line storage, widening, removal of P rich sediment and replacement with retentive materials (allowing nutrient stripping, sediment deposition and/or reuse).

These BMPs are used in various combinations to achieve the desired outcome. Figure 6-10 shows a set of point source and diffuse source BMPs to reduce P export from farms.

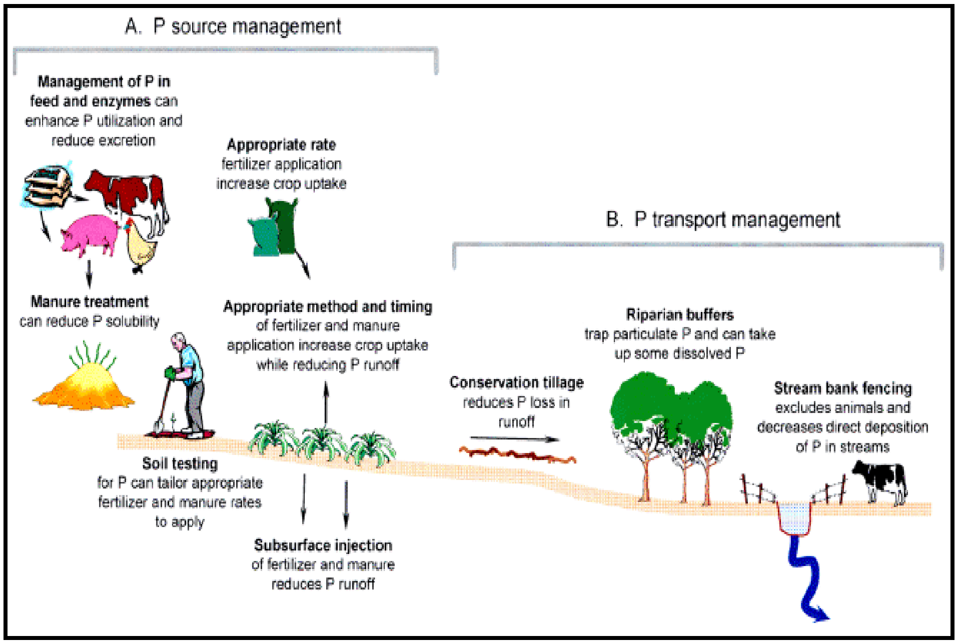


Figure 6-11 Management of Phosphorus Sources and Transport on Farms (http://www.ribbonsofblue.wa.gov.au)

In this study fourteen BMPs have been identified that are suitable for rural drainage and can be used by farmers and growers of the area:

1 Soil Amendment & Fertilizer Management
2 Riparian Buffers
3 Perennial Vegetation
4 Effluent Management
5 Control Stock Access
6 Irrigation Management
7 Retention Basin (Pond)
8 Detention Basin
9 Infiltration Basin
10 Sedimentation Basins / Traps
11 Spoil Management
12 Constructed Wetlands
13 Waterway Restoration / Living Streams
14 In-stream Structures

In the following sections, these BMPs are described in detail.

6.2.1 Soil Amendment & Fertilizer Management

Effective fertiliser management involves knowing when, where and how to apply the right fertilisers at the right rate to supply the correct nutrients to maintain production, reduce fertiliser expenses and minimise off-farm environmental effects.

Fertiliser management include:

- Conducting regular soil and/or tissue testing to determine the required nutrients to meet crop, pasture or animal needs;
- Applying fertiliser after the break of season, preferably in split applications;
- Applying fertilisers in spring when nutrient requirements are greatest;
- Having buffers between fertilised areas and watercourses;
- Calibrating the fertiliser spreader;
- Avoiding fertilising when intense rainfall is forecast;
- Avoiding fertilising firebreaks;
- Applying nutrients according to the recommendations of soil or tissue testing;
- Providing covered areas for stored fertiliser; and
- Using nutrient budgeting in making fertiliser decisions

Soil amendments and slow release fertilisers include:

- Coastal superphosphate. Old Coastal Superphosphate is a slow release fertiliser suited to the leaching grey sandy soils of the Swan Coastal Plain. As this product is no longer on the market there is a need for a slow release fertiliser for sandy soils in high rainfall zones. A 50% P reduction is possible with slow release P fertiliser per ha.
- RedCoat. Bauxite residue from alumina refining is used to coat granules of single superphosphate to reduce the leaching of phosphorus in coarse, sandy soils for pastures in high rainfall areas of Western Australia. The bauxite residue coating reduces the water solubility of the fertiliser and maintains the supply of phosphorus near plant roots in a manner that is more effective than single superphosphate in both the year that it is applied and subsequent years. This product is not currently on the market. Redcoat fertiliser use has 50% P reduction per ha.
- Lime Reverted Superphosphate. The process of reversion (whether done with limestone, serpentine or dolomite) changes the chemical form of the phosphorus and neutralises any excess acid. In super, virtually all the

phosphorus is present as highly soluble mono-calcium phosphate; in reverted products it is largely present in the less soluble di-calcium phosphate form. Thus about 85% of the total phosphorus in superphosphate is water soluble but this is reduced to about 10-20% in reverted products. This product is not currently available in Western Australia.

- Soil amendment – Alkaloam™. This practice involves the application of high P fixing materials such as Alkaloam™ to sandy soils to restrict phosphorus leaching. Sandy soils are naturally nutrient deficient and have very little capacity to retain applied fertilisers. Leaching of fertilisers applied to sandy soils is high but with the addition of a soil amendment such as Alkaloam™, the phosphorus retention capacity of soils can be greatly increased. Typical application rates are 5 t ha^{-1}. At present this product is not available for widespread use. Soil amendment (in the form of Alkaloam™), provides between 30% and 50% reduction in phosphorus output.

Benefits

- Soil amendment and fertilizer management optimise agronomic production of pastures and crops.
- Proper phosphorus management on small farms is important for four reasons:
    - Improves crop quality.
    - Improves farm profitability.
    - Improves crop water use efficiency.
    - Protects the environment.
- Fertilizer management ensures that only as much N and P as the crops needed are applied.

Technical Considerations

- Apply fertilisers after the break of season preferably in split applications.
- Apply fertilisers in spring when nutrient requirements are greatest.
- Have buffer areas between fertilised areas and watercourses. Do not fertilise the bottom 20 m of bays in flood irrigation.
- Calibrate fertiliser spreader.
- Avoid fertilising firebreaks.

- Apply nutrients according to the recommendations of soil or tissue testing; Use nutrient budgeting in making fertiliser decisions.
- Sufficient adsorption of the phosphate onto the iron oxide in the residue could be achieved by as little as 5-20 t ha^{-1}, with higher application rates used in areas of Phosphorus richness, such as effluent ponds.
- Soil nitrogen is frequently present in soil organic matter and is not available for plant uptake or leaching unless mineralised to nitrate or ammonium. In years when drainage volumes are low, N fertiliser can be utilised without impact on waterways. In low drainage years, nitrate may accumulate in soil, and be displaced in subsequently higher drainage years (Ridley *et al*., 2001). The cumulative nitrate load in a waterway will depend on the cumulative intensity of grazing and fertiliser use in a catchment.

Monitoring and Maintenance

- Conduct regular soil and/or tissue testing to determine the required nutrients to meet crop, pasture or animal needs
- Excessive levels of nutrients e.g. N and P encourage undesirable algal blooms and aquatic weed growth in surface waters. When the nutrients are used up, this growth dies and uses oxygen as it decays. As a result, the receiving waterway has less dissolved oxygen, creating an unfavourable environment for fish and other aquatic life.
- Algal blooms from increased nutrient levels in the waters. Moderately high algal productivity will generally exist with TP in the range of 20 to 50 $\mu g\ L^{-1}$ (Gilliom, 1984; Simpson and Reckhow, 1979). TN to TP ratios should be maintained above 10:1 to prevent blue green algae. The Peel Inlet and Harvey Estuary have suffered from severe toxic algal blooms over many years, principally driven by the input of phosphorus from a largely rural catchment.
- Nitrogen applied at agronomic rates will minimize the build up of soil organic nitrogen. Nitrates leached beyond the root depths of the crop to be grown during the following season will be susceptible for transport to the ground water.
- Test the nutrient levels of soils (at the same location) every 1–2 years and adjust fertiliser applications accordingly.

Cost Estimates

AlkaloamTM (for a spread rate of 10 t ha^{-1}) \$194 cost ha^{-1} (URS, 2005)

Redcoat Fertilizer (ha^{-1} $year^{-1}$) \$15 (URS, 2005)

Research and Development

- Recent research internationally and in south eastern Australia has identified N losses to groundwater, particularly from preferential flows through large soil drainage pores or macropores (Rasiah *et al*., 2003; Rassam *et al*., 2003), through mole and tile drainage systems under dairying (Eckard *et al*., 2004; Monaghan *et al*., 2005), under irrigation (Mundy *et al*., 2003), and from sheep-grazed pasture (Ridley *et al*., 2001).
- The Department of Agriculture, Western Australia with Alcoa World Alumina Australia Ltd have investigated the potential use of bauxite residues as soil amendments for the poor, acidic, sandy soils of the Swan Coastal Plain. Regional waterways, especially the Peel Inlet and Harvey Estuary. Extensive laboratory, field and catchment-scale trials have repeatedly shown the ability of soil amendment with fine bauxite residue (now trademarked in this context as Alkaloam^{TM}) to reduce the leaching of nutrients to sensitive regional waterways by up to 75%, while at the same time, increasing pasture productivity by up to 25% (up to 200% in well-controlled experimental situations). A new fertiliser which combines a traditional phosphatic fertiliser with AlkaloamTM is also being examined in partnership with the fertiliser industry.
- In early 2001 a fertiliser management project for Potato Growers in the Buayanyup catchment was funded by the Water Corporation (http://www.virtualcentre.org/en/dec/manure/img/Slide31.GIF) to assess groundwater nutrient contributions from summer and winter potato paddocks, followed by the implementation of strategies to reduce nutrient discharge from high risk sites. The project demonstrated that changes to fertiliser inputs and management of high risk sites can greatly reduce nutrient discharge from horticulture paddocks with increased nutrient use efficiency
- Summers *et al*., 2002, report that the phosphorus retention of AlkaloamTM has been found to be very high and long-lasting when examined at the laboratory, sub-catchment and catchment scales. Trials in Meredith

Catchment showed that AlkaloamTM increases pasture production when applied at rates between 5 and 80 t ha^{-1}, with most benefit occurring at rates equivalent to traditional agricultural liming rates. Phosphorus loss to surface drainage from the catchment treated with 80 t^{-1} ha^{-1} bauxite residue (4.2 kg P ha^{-1}) was reduced by 70% when compared with the untreated catchment (13.8 kg P ha^{-1}). A reduction in P loss of this magnitude continued for five years until monitoring ceased.

Barriers

Negative press stopped the use of iron oxide residue from bauxite mining; know as 'AlkaloamTM', to control Phosphorus. Government should provide subsidy for 'AlkaloamTM', to control Phosphorus. Sufficient adsorption of the phosphate onto the iron oxide in the residue could be achieved by as little as 5-20 tonnes per hectare, with higher application rates used in areas of Phosphorus richness, such as effluent ponds.

Professional fertiliser advice regarding application rates was also identified as an important incentive in Torbay catchment (Duxbury, 2005).

6.2.2 Riparian Buffers

A riparian buffer is an area of trees, shrubs, grasses or other vegetation that is (i) at least 11 m wide, (ii) adjacent to a body of water, and (iii) managed to maintain the integrity of stream channels and shorelines. A riparian buffer reduces the effects of upland sources of pollution by trapping, filtering, and converting sediments, nutrients, and other chemicals. It also provides wildlife habitat (Chesapeake Bay Program, 2006).

Grass, plants, and the soil that they grow in act as filters for stormwater, capturing the sediment and particulates. A buffer slows down the flow of stormwater, allowing for natural processes of evaporation, transpiration and vegetative uptake to occur. All of these reduce the total amount of runoff that reaches the waterways. The slower the flow in a grass swale, the more pollutants will be removed from stormwater through sedimentation and the straining of surface runoff through the vegetative cover. Also, the slower the flow, the more time stormwater has to infiltrate into the ground. The ultimate in slow flow is a swale that acts as a linear detention basin.

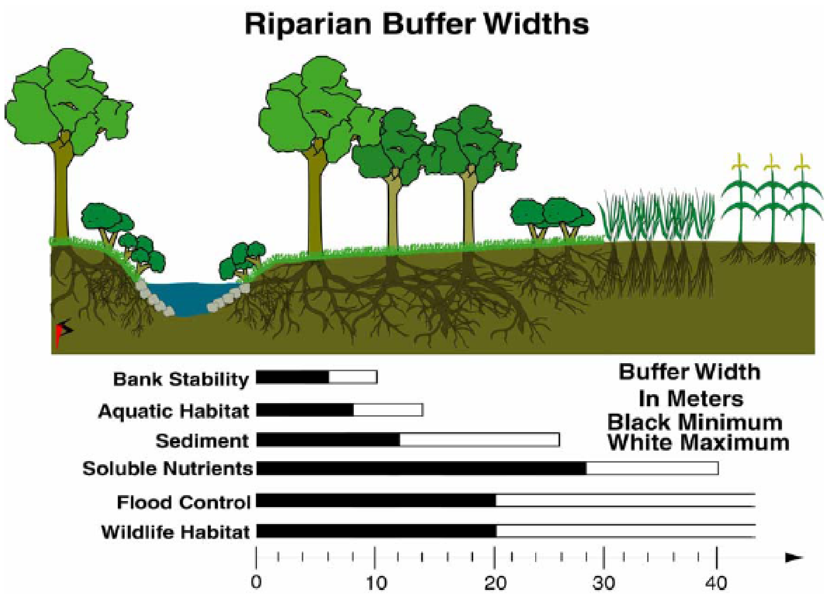


Figure 6-12 Riparian Buffer Widths (by Peter Schultz taken from Dept. of Natural Resource Ecology, Iowa University)

A riparian forest buffer is an area of trees and shrubs located adjacent to streams, lakes, ponds, and wetlands. Riparian forest buffers of sufficient width intercept sediment, nutrients, pesticides, and other materials in surface runoff and reduce nutrients and other pollutants in shallow subsurface water flow. Woody vegetation in buffers provides food and covers for wildlife, helps lower water temperatures by shading waterbody, and slows out-of-bank flood flows (US Department of Agriculture, 1998).

A filter strip is an area of grass or other permanent vegetation used to reduce sediment, organics, nutrients, pesticides, and other contaminants from runoff and to maintain or improve water quality. Filter strips intercept undesirable contaminates from runoff before they enter a waterbody. They provide a buffer between contaminant source, such as crop fields, and waterbodies, such as streams and ponds.

A percolation trench is a rock filled trench that temporarily stores stormwater and percolates it into the ground. A percolation trench typically serves small impervious tributary areas of two hectares or less.

Benefits

- Riparian buffers help improve water quality by filtering or retaining sediment particles and chemicals, such as nutrients and toxics, preventing them from reaching the waterways. Roots of buffer vegetation create breaches in the soil, promoting rainwater infiltration and groundwater recharge while moderating peak runoff flows in adjacent streams and subsequent erosion. Roots also stabilize stream banks, further preventing bank erosion. Soil within the buffer is stabilized through the accumulation of multiple layers of dead and decaying leaves, branches, twigs and other organic matter. Riparian zones also provide wildlife habitat in the vegetation and aquatic habitat in the adjacent streams. Shade from trees, roots, and falling leaves all play their roles in creating habitat for aquatic creatures.

- Riparian buffer strips with deep rooted perennial vegetation serve to lower the water table and consequently reduce the flow of salt into streams from sub-surface flow.
- Riparian zones can provide a protective buffer between streams and adjacent land-based activities by removing nitrate from shallow groundwater flowing through them. Increased inputs of nitrate to natural waters contribute to problems including reduced water clarity and growth of weeds and algae.
- Riparian vegetation assists in decreasing bank erosion through the soil binding properties of the root matrix.
- Protects aquatic ecosystems such as stream channels & water bodies. Land-based animals use the riparian zone to shelter, hunt and breed.
- Reduces discharge of pollutants from storm drainage systems to the Maximum Extent Practicable (MEP).
- Riparian buffers reduce Nitrogen and are effective in immobilizing, storing, and transforming chemical inputs (fertilizers, pesticides, etc.) from uplands.
- A riparian buffer reduces Phosphorus and other chemicals from upland sources of pollution by trapping, filtering.

Figure 6-13 Young Vetiver Grass hedge is trapping sediment on the floor of a waterway (http://www.virtualcentre.org/en/dec/manure/img/Slide31.GIF)

The type, size and effectiveness of riparian buffers vary based on the location, environmental management needs and landowner needs.

- Nitrogen

Riparian forest buffers can reduce N by 40 - 100%, Grass buffers can reduce N by 10 - 60% (improved with vegetation). In experimental studies of grass and combined grass and woody buffers in Iowa, USA, (Lee *et al*., 2003) report trapping efficiency of 80-94% total nitrogen (TN).

- Phosphorus

A riparian buffer reduces the effects of upland sources of pollution by trapping, filtering, and converting sediments, nutrients, and other chemicals.

In experimental studies of grass and combined grass and woody buffers in Iowa, USA, Lee *et al*., (2003) report trapping efficiencies of 78-91% for total phosphorus (TP) loads

- Sediments

Reduction of sediments depends on how the riparian buffer is well managed. Under the Soil and Land Conservation Act 1945, land owners and occupiers must prevent uncontrolled erosion on their property. Compliance with this requirement will not only prevent silting of the waterway but also allow maximum opportunity for nutrient uptake by pastures.

In experimental studies of grass and combined grass and woody buffers in Iowa, USA, Lee *et al*., (2003) report trapping efficiencies of 97-99% for sediment loads. Riparian buffers on banana plantations in Far North Queensland, Australia, monitored over three wet seasons, were observed to trap more than 80% of the incoming coarse sediment load, but only 30-50% of the fine suspended sediment load and its associated nutrient (McKergow, 2002). In an experimental study, Mickelson *et al*., (2003) reported sediment trapping efficiencies of 71% and 87% across grass buffer widths of 4.6 and 9.1m, respectively.

Grass Swales-Removal rates exceeding 80% of TSS are suggested by some researchers. Others suggest lower removal rates, on the order of 20 to 40% (UD&FCD, 1992). The higher rates may be possible when soils have very high infiltration rates and very slow flow velocities occur (i.e., less than 0.15 m s^{-1}). Grass swales appear to be best suited when terrain slopes are less than 3% to 4%, although some have suggested their use with terrain slopes as high as 6%.

Technical Consideration

- Riparian buffers are effective when placed upstream of water bodies. The type, size and effectiveness of riparian buffers vary based on the location, environmental management needs and landowner needs. Stock access to riparian land needs to be managed
- Trees should be planted away from drain so that branches and leaves do not fall in the drain potentially causing blockage and subsequent local flooding. Small shrubs, less than 1 m height, should be planted closer to the edge of the drain, native reeds and rushes on the drain sides and disturbance tolerant small shrubs/heath plants along the access track.
- Trees, shrubs, perennial grasses or legumes should be kept along steep slopes, drainage channels or ditches, and around bodies of water. Native plants generally survive best. The proper width of "buffer strips" of vegetation between land that is being used and water courses will depend on type of soil, degree of slope, and type of vegetative cover.
- Filter strips slow the velocity of water, allowing the settling out of suspended soil particles, infiltration of runoff and soluble pollutants, adsorption of pollutants on soil and plant surfaces, and uptake of soluble pollutants by plants.

- Changes in land use management can influence riparian vegetation composition, density and vigour, flow modifications (diversions, storage, reservoir release schedule modifications based on the operational hydrology), flood control measures, road closures/stabilization, hillslope erosion processes and other process influencing river stability.
- For sediment control, widths may vary, with a minimum buffer of 23 m suggested for coarse sand removal, 139 m strip for silt control, while control over clay requires wide scale land management strategies and cannot be met by simple buffer zones.
- Riparian buffers should be 10-20 m long for Nutrient control; 20-60 m for Sediment Control.
- Stock access to riparian land needs to be managed.
- Plant trees away from drain so that branches and leaves do not fall in the drain potentially causing blockage and subsequent local flooding. Planting small shrubs (less than 1 m height) closer to the edge of the drain, native reeds and rushes on the drain sides and disturbance tolerant small shrubs/heath plants along the access track.
- Plants with high root to shoot ratios retain sediments (and thus reduce resuspension) better than those with lower root biomass. The main locations on which plantings have occurred include areas adjacent to drains either on private property, shire road reserves or drainage reserves as well as along fence lines, road and rail reserves.
- If not maintained properly, they reduce flow area creating flood hazard.
- River and creek banks are vulnerable to erosion from fast flowing water. Riparian vegetation protects the river channel from erosion. Dillaha *et al*., (1989) showed that riparian buffers are ineffective for particulate removal when runoff is concentrated in natural drainage pathways. When overland flow becomes concentrated, its velocity and depth increase and trapping declines, effectively the flow by-passes the grasses that trap particulates.
- Vetiver Grass has a highly beneficial role in nutrient attenuation from agricultural properties; however more education and trials need to be instigated to make adoption successful.

Monitoring and Maintenance

Riparian buffer systems need regular inspections, to ensure vegetation cover is adequate. Regular sediment removal and inspection and repair of any scour and erosion areas should be undertaken, including assessment after large storm events. Rubbish and other debris should also be removed on a regular basis.

Cost Estimates

The costs for the design, construction, operation and maintenance of drains are high for stakeholders. Studies have demonstrated the need for ongoing maintenance including weed and pest control, periodic harvesting of vegetation, and measures to combat channelisation and stream bank instability (Dillaha *et al*., 1989; Lovett and Price, 1999; Parkyn, 2004).

A cost of \$1,500-2,700 ha^{-1} for a treatment where filter strip run alongside a watercourse including a 30 m wide strip wide strip with a gate and alternate water supply source (Rendell, 1996-Victoria).

Riparian management includes the fencing of streams, their rehabilitation and revegetation, stock exclusion, construction of stock and vehicle crossings and the provision of off-stream watering points. Cost within a farm - \$3,975 km^{-1} for streams of order 3 and above, \$5,030 km^{-1} for order 2 streams and \$6,110 km^{-1} for order 1 streams. Ongoing costs of \$475, \$225 and \$175 km^{-1} yr^{-1} for order 3, order 2 and order 1 stream, respectively (URS, 2005).

Research and Development

Many Australian regional and catchment-based management plans include the establishment of riparian buffers as key management actions (e.g., Lachlan Catchment Management Board, 2003). Effectiveness of buffer strips in reducing sedimentation and pollution input to streams was demonstrated in high-rainfall agricultural areas of North Queensland. The strips can trap about 70-80% of sediment, except where loading is too high (e.g. paddock draining at a single point).

In the United States, for example, the Chesapeake Executive Council plan to establish approximately 41,000 km of riparian forest buffers in the Chesapeake Bay basin area in an attempt to improve stream water quality (CEC, 2003).

In New Zealand, the Ministry for the Environment (2000) has recommended the establishment of riparian buffers as an essential element in the sustainable management of water quality in rural New Zealand.

Barriers

- Riparian buffers may use land that can otherwise be utilised by the landowner. Benefits to individual farmers need to be outlined.
- Monetary assistance, training courses, and demonstration trials were indicated as the most popular incentives that would encourage farmers to change. Interestingly tax exemptions, compensation for loss of land, and subsidies for soil testing costs ranked low on the favoured list (URS, 2005)
- Provide technical help and information and follow up.
- Show benefits through education programs, workshops and Research & Development

6.2.3 Perennial Vegetation

Perennial vegetation comprises of plants with a life cycle extending for more than 2 years and that continue to live from year to year.

Benefits

- Perennial pasture systems can be significantly more productive than annual systems, and use larger amounts of water than annual systems which can reduce water logging and salinity problems.
- Perennial pastures have deep rooting systems: they are able to stay green later in spring, and therefore limit erosion.
- They have the ability to intercept nutrients that have leached below the shallow root system of annual pastures and provide opportunities for immediate water and nutrient uptake when there is un-seasonal weather.
- Replacing annual pastures with perennial pastures can help in the uptake of phosphorus and other nutrients.

Perennial pastures appear to offer an opportunity to reduce nutrient loss whilst increasing farm productivity through high water use, deeper rooting systems and lower nutrient requirements (Knight, 1990). Previous research has compared perennial systems and their attendant nutrient losses (Ridley *et al*., 2003), however no research has compared nutrient losses from annual and perennial pasture based systems. Productivity returns are more certain, but nutrient export reductions of around 20-30% are expected (Keipert *et al*., 2007)

Costs are variable depending on vegetation type. Perennial pasture capital cost \$250 ha^{-1}, annual cost \$30 ha^{-1} (URS, 2005).

Technical Considerations (Source: DPI, 2005)

Breeding ewes and rams should be put into paddocks with productive perennial shrubs and grasses (e.g. salt lake or river frontage) and wethers put into more seasonal country (e.g. wanderrie grass).

Areas where the perennial vegetation has been degraded, but the soil surfaces are still largely intact, can be improved by careful management including:

- Reducing total grazing pressure (feral as well as domestic);
- Grazing different animals (e.g. Cattle in lieu of sheep); and
- Fencing and water relocation can also contribute to pasture re-establishment.

Some species of perennial legume pasture available to land managers include: Lucerne, strawberry clover (Trifolium fragiferum), white clover (Trifolium repens) and red clover (Trifolium pratense).

In saline area a mixture of saltbush (Artiplex sp.), bluebush (Maireana brevifolia), goledn wreath wattle (Acacia saligna), tall wheatgrass (Thinopyrum elongatum) and puccinellia (Puccinellia ciliata) would be beneficial.

Bluebush (Maireana brevifolia), Wavy leaf saltbush (Artiplex undulata) and River saltbush (Artiplex rhagodioides) is recommended for salt land in the Wheatbelt of WA.

Salt-water couch (Paspalum vaginatum) thrives well in bogs, gullies and seepage areas. Samphires are a group of succulent, highly salt tolerant perennial shrubs.

Monitoring and Maintenance

Growth of perennial vegetation such as phalaris and lucerne is improved by rotational grazing and rest periods for plant recovery (Department of Primary Industries, 2008). There are three principles associated with rotational grazing, these are:

- Maximising light interception;
- Encouraging tillering and stem production;

- Recovery after grazing

Rotational grazing management for lucerne is also dependent on short grazing periods followed by long rest periods for plant recovery. The ideal arrangement for sheep grazing is a 6 paddock system where at least 5 weeks of recovery can be achieved between grazing periods. If cattle are being used, the number of paddocks can be reduced as cattle do not graze lucerne as closely as sheep.

Lucerne is characterized by its level of winter dormancy with some cultivars having high winter dormancy (little growth in winter) whilst others have lower winter dormancy (higher winter growth). Grazing management for lucerne should take into account seasonal requirements, the cultivar's level of dormancy, the livestock production system and the potential for maximum production occurring in the spring and summer seasons.

Research and Development

New work is being done in Torbay Catchment to provide an insight into ways that key targets could be met. For example, what would the catchment look like if the target of 85% perennials was achieved through perennial pastures or through 55% perennial pastures and 35% agroforestry.

The Busselton Environmental Improvement Initiative (EII) by the Water Corporation focussed on assisting landholders to significantly reduce nutrients and other contaminants which drain from their properties into surface and groundwater systems and eventually reach southern Geographe Bay. Over two years, funds have been allocated to the establishment and management of deep-rooted perennial pastures in six EII catchments.

A variety of EII projects have targeted cattle grazing and other high diffuse nutrient sources. The projects included a nutrient management project which provided soil testing and fertiliser advice, funding for fencing stock out of streams and a perennial pastures project.

Information on economic and management decision making is not readily available for the individual landholder. A perennial pasture support program was a key action recommended to the Watershed Torbay steering committee (Duxbury, 2005).

6.2.4 Effluent Management

Effective effluent management includes the collection, conveyance, treatment, storage and reuse of solid and liquid wastes. Typically effluent management would be carried out for piggeries and dairies where wash down results in a requirement to store, contain and possibly treat effluent prior to discharge or irrigation. Animal effluents can contain high concentrations of nutrients and bacteria and therefore represent a significant risk to water quality if not handled correctly.

Benefits

Animal Waste Management Systems are designed for the proper handling, storage, and utilization of wastes generated from animal confinement operations and includes some means for collecting, scraping, or washing wastes from confinement areas into appropriate waste storage structures. Lagoons, ponds, or steel or concrete tanks are used for the treatment and/or storage of liquid wastes, and storage sheds or pits are common storage structures for solid wastes.

Livestock waste management system has an efficiency of 75% for Phosphorus and Nitrogen. Poultry waste management system has efficiency of Phosphorus 14%, and Nitrogen 14%. Barnyard Runoff Controls has efficiency of Phosphorus 10-20%, Nitrogen 10-20%. For dairies approximately 10-15% of the nutrient problem is located in and around the dairy shed. The remaining 85-90% is essentially a diffuse nutrient problem over the farm. The maximum nutrient reduction from effluent management at the dairy shed is about 10% of that produced on the farm. For fully shedded industries such as piggeries and poultry farms, 90-100% of effluent produced nutrients could be managed.

Technical Considerations

- Requirement to store, contain and possibly treat effluent from dairies, piggeries, feedlots and poultry prior to discharge or irrigation.
- The application strategy for manure is important. Manure should be applied at least 30 m from waterways. Apply fertilisers at recommended rates for crop production. Credit fertilisers contributions from manure and other organic wastes. Band fertilisers below the soil surface or broadcast and incorporate it.
- Barnyards, stockyards, feeding and watering areas should be located well away from surface waters, to prevent runoff from reaching them.

- Applying effluent shandied with irrigation water immediately following grazing is recommended, as there is an opportunity to utilise the nutrients in the regrowth of plants. It also enables pasture palatability to return before the next grazing. A withholding period of 14 days is recommended following effluent application. A longer period may be required following the application of slurry.
- Animal diseases can be transmitted to humans through contact with animal faeces. Runoff from fields receiving manure will contain extremely high numbers of bacteria if the manure has not been incorporated or the bacteria have not been subject to stress.
- Apply manure evenly as a fertilizer to pastures, fields and gardens. Apply only as much as the crop or pasture can use. Excess manure will wash off into surface waters or leach into groundwater systems. Till manure evenly into soil whenever possible to maximize nutrient use and minimise runoff. The soil generally has the capacity to adsorb phosphorus leached from manure applied on land but phosphorus can be transported by eroded soil. Nitrates are easily leached through soil into groundwater or to return flows.
- The West Australian guideline for piggeries in Western Australia recommends that the degradable organic matter loading rate should not exceed 30 kg BOD/ha/day to avoid offensive odours. Heavy metals applications should not exceed Australian and New Zealand Environment and Conservation Council (ANZECC) guidelines for fresh and marine waters. The guideline has a section on treated effluent reuse. Table 5 is used to determine maximum nutrient loading rates.
- Dairies should follow the Dairy Effluent Management Guidelines for the management of dairy effluent. Particular care should be taken to site dairy sheds and effluent ponds on higher ground away from streams. Effluent ponds should be excavated into clay subsoils, as trials have shown that groundwater pollution occurs near ponds excavated into sandy soils. The treated liquid effluent should be irrigated or spread onto pastures on higher ground that is not inundated in winter (Dept of Agr. Bulletin 4513).

Monitoring and Maintenance

Monitoring is essential both prior to and after installation of a denitrification trench. Prior to installation groundwater monitoring bores determine the concentration of nitrate and the flow pathway of the groundwater. After the trench has been constructed regular monitoring should be carried out to determine the effectiveness of the trench. Once established, denitrification trenches remain effective for a number of years before the sawdust needs to be renewed. Ongoing research in New Zealand has shown that the sawdust remains over 90% effective for at least 5 years (Schipper *et al*., 2001). Calculations for the Busselton trench indicate it could have a lifetime of up to 20 years providing an effective and long term solution to groundwater nitrate management (Fahrner, 2002).

Test soil for nutrients and apply the recommended amount. Credit fertilisers contributions from manure and other organic wastes. Band fertilisers below the soil surface or broadcast and incorporate it.

Test the nutrient levels of soils (at the same location) every 1–2 years and adjust fertiliser applications accordingly. Apply only as much N and P as the crops need.

Cost Estimates

The cost of phosphorus retention from effluent management systems in dairies was considered in the URS (2005) assessment of factors motivating landholders and is tabled below showing that the cost was estimated to be $200 per cow which translates to about $30,000 on the median herd size of 150 milkers and this agrees with the upper cost of a typical effluent system noted above. The cost per unit P retained from reaching the estuary is $2,570 kg^{-1} based on 350 kg retained from reaching the estuary and $30,000 per dairy property.

Level 1 treatment costs $25,000 for a dairy and up to $350,000 for a piggery (URS 2005).

Research and Development

1. Department of Agriculture provided targeted assistance to intensive agricultural activities in the Peel-Harvey Coastal Plain Catchment 2006 (Quoted as Appendix G in Peel-Harvey WQIP).

Nineteen dairies operating in the Peel-Harvey catchment that were surveyed had full effluent management systems. Concurrent with this project was a general assistance package for effluent management being run by Dairy Australia and administered through Dairycatch. The cost of effluent management systems were approximately $20,000 to $30,000 and assistance of $4,000 was available through this CCI project.

The cost of implementation of the effluent management system varied because of site specific factors which could be capitalised on such as natural fall in the landscape reducing the need for pumping and the availability of existing irrigation. Although most of the properties had some form of existing effluent management system, there were few with complete systems or with adequately sized systems.

The dairy properties surveyed were assessed for nutrient balance and the surplus was calculated to be a total of 79,460 kg of phosphorus and the total from all 33 was estimated to be 138,000 kg surplus. The amount of effluent captured in the effluent ponds was estimated to be less than 10% of the surplus which would be 13,800 kg.

2. DairyCatch, is a partnership between several groups including: Western Dairy, Geographe Catchment Council, the departments of Agriculture and Environment, the WA Farmers Federation, the South West Catchment Council, the Water Corporation, Harvey Water, the Dairy Product Manufacturers Association and Dairy Australia.

DairyCatch has targeted the issues of effluent management, nutrient management and water use efficiency, recognised as having the greatest short-term impact on the sustainability of dairying in WA. The program has five modular components that operate concurrently and complementarily. These include the planning support & implementation grants scheme, the monitor farm network, benefit to cost analysis based on case studies and the documentation of environmental best practice guidelines.

Since December 2003, a large proportion of dairy farmers have participated in the grants scheme and this has reduced the risk and extent of degradation of our natural resources. The DairyCatch experience has led to over nine million dollars of new NRM-related research funding being invested across the southwest. DairyCatch was independently reviewed in March 2005 and found it to be one of the most successful programs of its kind in the country (http://www.peel-harvey.org.au/content/cci_projects/cci_p4_bpap.asp).

The Busselton EII project by the Water Corporation provided funding for farmers to improve waste management on their farms. In early 2001 two neighbouring properties in the Upper Vasse catchment were granted funding of $5,103 to establish a dairy wastewater trafficable sump and dairy solids composting system.

Through the project assessment process, the Busselton Local Advisory Group calculated that this dairy waste solids collection and composting system represented approximately 20.4 tonnes of organic nitrogen $year^{-1}$ and approximately 4.1 tonnes of organic phosphorus/year. Consequently, the solid dairy wastes were considered to be a significant source of concentrated nutrients and the project was therefore eligible for funding.

The project consisted of a concrete trafficable sump for solids collection at one property and a series of windrow compost heaps to convert the dairy wastes into a valuable soil conditioner on the neighbouring property. Specialist advice was supplied to the compost operators from the Water Corporation staff who have been converting human biosolids from Perth wastewater treatment plants into compost products for the past five years.

As a result of the specialist advice, compost quality was improved through the addition of mulched green waste from the Busselton landfill site, permanent sprinkler water systems for the windrows and a series of site specific guidelines to ensure that temperatures in the compost rows are regulated. The result is a natural organic fertiliser that improves pasture condition and enables the owners to retain their certification as registered organic beef and sheep producers.

4. Another example of dairy wastewater project funded through the EII is a property in the Buayanyup catchment. This project involved installing a concrete trafficable sump to intercept the washdown water and remove a large percentage of the waste solids. Figure 1 shows the quantity of washdown waste that can accumulate around the dairy. Figure 2 shows the trafficable sump collecting the wastewater for storage and separation. A travelling irrigator, wastewater pump and associated pipework were purchased to enable irrigation of the filtered wastewater onto summer pastures. The total implementation budget for this project was $16,750 with 50% being covered by an EII grant and 50% covered by the farmer.

It is estimated that the washdown waste from this dairy shed represented approximately 833 kg total nitrogen/year and approximately 145 kg total phosphorus/year. Consequently, the site was considered to be a significant source of concentrated nutrients within the Buayanyup catchment and was considered an appropriate use of EII funds.

The total cost of EII funded dairy wastewater management projects has ranged from just a few thousand dollars to nearly $5,000 with 50% being contributed by the farmers. Most projects were costed around $20,000 for their total project budget. Each of these properties represented a significant source of nutrients which, now with the appropriate management, will collectively lead to a considerable reduction in nutrients entering Geographe Bay.

Thirty dairy wastewater management projects have deflected a combined estimated 44.4 tonnes of nitrogen and 7.5 tonnes of phosphorus per year away from discharge to shallow groundwater or waterways (Hajkowicz, *et al*., 2000b).

6.2.5 Control Stock Access

Stream protection with fencing involves the fencing of narrow strips of land along streams to completely exclude livestock. The fenced areas may be planted to trees or grass. Allowing stock access to ditches shortens their life considerably and results in higher maintenance costs.

Benefits

Uncontrolled stock access to an un-vegetated drain in the Coolup Drain Catchment is a serious cause of sediment loss and has been shown to increase sediment in a drain in the Coolup Catchment by up to 13 times.

Fencing off the drains stops damage and defecating into them by stock. Leaching of N frequently occurs via high N concentrations from grazing animal urine patches, rather than from direct fertiliser losses

Fencing out stock can markedly improve waterway health and water quality.

A 60% reduction in Phosphorus, 60% Nitrogen and 75% reduction in sediments is possible with control stock access. Reduction in the need to de-silt the drains, which reduces maintenance costs.

Technical Considerations

- Consideration should be given to alternative watering and fencing involving narrow strips of land along streams to exclude livestock. The fenced areas may be planted with trees or grass, but are typically not wide enough to provide benefits of buffers. The implementation of stream fencing should substantially limit livestock access to streams, but can allow for the use of limited hardened crossing areas where necessary to accommodate access to additional pastures or for livestock watering.
- Rotational grazing and alternative watering with cross fencing systems can be used to create paddocks to enable rapid grazing of small areas in sequence. Once an area is intensively grazed of most vegetative matter, the animals are

moved to another paddock to enable recovery of the pasture grasses. This BMP is beneficial in removing animals from stream areas, but detrimental in that the animal stocking rate per hectare frequently increases substantially, thereby increasing the quantity of animal waste deposited per hectare of pasture.

- Fencing and planting of shade-providing vegetation along drains that run through levees to river is encouraged with gates installed at the point selected for stock access. The shade prevents excess plant and algal growth, reducing the amount of clogging in drains and removing the need to spray.
- Unrestricted stock access generally has a number of damaging effects:
- Grazing and trampling vegetation;
- Preventing regeneration;
- Compacting soil;
- Increasing erosion and bank slumping;
- Transportation of weed seeds in fur and faeces; and
- Contributing nutrients and disease organisms through stock urine and faeces.
- Fences should be placed well out of the floodway to avoid loss and damage during high flows. For shallow river valleys, such as those on coastal plains, fences can be located on the crest (the top of the floodway banks) ensuring that the floodway is well protected with fringing vegetation. Fences that run parallel to the direction of a flood are less likely to be damaged by flooding than those that span the floodway and floodplain. Keeping the number of fences that cross the river to a minimum is advisable.
- Electric fencing is a common choice as it can cost half that of conventional fencing and has the added benefits of being quicker to erect, moveable and can fence along curves most effectively. A single, well-placed electric wire will allow grazing under the fence but not through it. Dairy cows and cattle generally will only need one ‘hot’ wire while sheep will require at least four wires on an electric fence.
- Provide off-stream watering for cattle and limit access of cattle to the drain. Leave a buffer zone adjacent to the drain. Establish watering and feeding areas for animals away from slopes leading to water bodies. If animals must

be watered at streamside, use a ramp-fence system. Keep the area cleared of manure.

Monitoring and Maintenance

- Regular inspection of drains to ensure the integrity of the stock control measure.
- Algal blooms from increased nutrient levels in the waters.
- Unmaintained fencing leads to stock access. This causes reduction in water quality of creeks, rivers, wetlands or marine waters and limits. Damage to fences may be caused by a number of factors including stock, flooding, fallen timber and fire. Proper maintenance may be hard to implement unless properly resourced.

Cost Estimates

Depending on the level of engineering required \$500 to \$1,000 per stock crossing is estimated. The materials for electric fences are generally in the range of \$500 - \$1,000 km^{1}, while a single hot wire fence may be well under \$500 km^{-1}. For conventional prefabricated fencing the cost of materials is generally slightly more expensive ranging from \$500 - \$1,500. Conventional wire fences can cost up to \$2,000 km^{-1} (Agriculture WA, 1999).

Contract fence construction cost was \$2,000 - \$2,500 km^{-1} and \$3,000 for stock crossing in 2004.

Research and Development

The River Action Plans by the Geographe Bay catchment Council assist landholders to protect and enhance of riparian vegetation and to reduce nutrients entering waterways and downstream wetlands and Geographe Bay.

They provide advice and funding for:

- Fencing of waterways;
- Construction of livestock crossings and erosion control measures;
- Weed control along waterways;
- Revegetating waterways; and
- Other benefits of restoring the waterway.

Barriers

Cost seems to be the most obvious issue. In the Peel-Harvey area almost 90% of the gazetted drainage system remains unfenced. It is suggested that the State Government, possibly via the Water Corporation CSO contribute towards a 'Peel Healthy Drains for Clean Water' program (Peel-Harvey Catchment Council, 2007).

6.2.6 Irrigation Management

Irrigated farming systems are generally managed significantly more intensively than dryland systems and are therefore often subject to elevated nutrient input levels. However, they are also often located on the better regional soils which may have a better ability or potential to retain phosphorus from leaching and attenuate phosphorus lost from the farming system than some of the other soil systems. Best practice irrigation system design includes: Whole farm planning, use of a qualified irrigation system designer, identification of appropriate irrigation sites and potential seepage areas, pre-installation soil management, calculation of irrigation requirements, maximisation of distribution uniformity, and automation of irrigation systems.

Benefits

- Improves application uniformity and reduce runoff and deep percolation.
- Minimise water losses in the on-farm distribution system.
- Reduce contamination of surface water by sedimentation
- Water Conservation
- Better crop yield.

Technical Considerations

- Over watering will result in water logging and yield losses on heavy soils, wasted water and unnecessary high pumping costs; and inefficient use of applied nutrients into the groundwater and wetlands adjacent to sandy soils.
- Reduce excess irrigation by changing application method (e.g., flood to sprinkle) or better matching irrigation to crop requirements.
- Upgrade supply channels to reduce losses to groundwater and evaporation
- No-till and other high residue management systems can reduce the amount and frequency of irrigation. In these systems, runoff is slowed and infiltration is

increased, surface evaporation is reduced, and the water holding capacity of the soil can increase over time.

- Schedule irrigation according to crop needs, soil water depletion, and water availability, accounting for precipitation and chemigation. Apply only enough irrigation water to fill the effective crop root zone.
- Line irrigation water delivery ditches to reduce seepage losses. Install pipelines to convey irrigation water where feasible.
- Avoid intentionally applying excess irrigation to leach salts until the growing crop has taken up fertilizer N. When leaching of soluble salts is necessary to maintain productivity, time leaching to coincide with periods of low residual soil nitrate.
- Install flexible membrane linings in earthen ditches and/or reservoirs.
- Install pressurised systems e.g. centre pivots, lateral moves, drip irrigation to replace surface irrigation. Upgrade nozzles and lowering of water points for centre pivots, lateral moves and other pressurised systems.
- Installation of automatic gates and valves can improve irrigation efficiency.
- Heavy soils, with low rates of soil-water movement, require closely spaced (2-6 m apart) subsoil drainage systems to provide sufficient water movement to control the effects of salt-water logging on pastures. Such close spacing using traditional buried pipe or tile drainage systems is impractical. As a result, mole drainage systems, used in other parts of the world for over 50 years, have gained popularity in recent years.
- Planting in Mulch - Planting a crop, such as wheat, in mulch is an excellent BMP. Mulch does not allow any drain water to leave the field during irrigation. After the soil is mulched the seed is planted below the mulch and into the mud where it germinates without further irrigation. By the time the first irrigation is needed the plant will have grown to almost 0.3 m high with a well-developed root system which reduces erosion. In addition the solid stand of the crop will act like a filter strip to slow down the water and reduce soil movement.
- Historically most irrigation in the SWIA has used surface flood systems for pasture production to support the dairy industry. In recent years, where pipe supply systems are available, there has been a transition to increased use of sprinklers and trickle systems with the growth in citrus, table and wine grape and vegetable cropping.

- Establishment of new recycling systems or significant upgrades to existing recycling systems to keep water on farm. Pump-back systems, which return drain water back to the irrigation ditch, will reduce the amount of silt leaving the field because a portion of the water is being recycled and used over. This too, can be listed as a very useful BMP but it comes with an added expense of labour and fuel required to pump the water back to the irrigation ditch.
- Sprinkler Irrigation, Drip Irrigation, and Level Basin Irrigation - High amounts of erosion usually occur during the first irrigation when a new crop is being germinated on recently worked soil. When a moveable sprinkler irrigation system is used to germinate the crop no drainwater is produced. A level basin irrigation system as well as a drip irrigation system also produces no drain water and growers need to understand that these can be considered as the ultimate BMP
- Salts significantly pollute freshwater ecosystems (and affect saltwater ecosystems). It adversely affects anadromous fish. Although they live in coastal and estuarine waters most of their lives, anadromous fish depend on freshwater systems near the coast for crucial portions of their life cycles.

Monitoring and Maintenance

- Scheduling and management of irrigation to reduce water reaching the watertable
- Seal leaking channels or storages to stop seepage.
- Monitor soil moisture by the feel method, tensiometers, resistance blocks, or other acceptable methods before and after each irrigation.
- Excess irrigation is contributing to drainage problem. Monitor effect of individual irrigation on water table and monitor fluctuation of water table throughout irrigation season and during times of no irrigation. Monitoring should include irrigation application method and uniformity of water applied. A water table profile and groundwater hydrographs of the drainage area should be studied. Rainfall and runoff should be monitored with groundwater table fluctuations.

Cost Estimates

Costs are extremely variable, installation of improved irrigation systems can sometime be a costly exercise, however, retro-fitting of specific management methods are quite cheap. It has been estimated that installation of a complete suite of

BMPs for a surface-irrigated dairy farm which would improve water and nutrient use efficiency markedly would cost in the order of $10,000. Individual BMPs (such as simple automation systems) would cost in the order of $500 - $1,000.

The typical costs as follows:

- Laser levelling are $1,500 to $3,000 ha^{-1}
- Automatic flood irrigations are about $160 to $240 ha^{-1}
- A water alarm system can be as low as $1,000 per unit.

Research & Development

1) Dairy Australia along with others conducted some research programs on the impact of nutrients on catchment and farm scale levels (http://www.chesapeakebay.net/pubs/waterqualitycriteria/doc- Ag_BMP_Defns.pdf).

. Some of the projects are:

- Future dairy farming systems in irrigation regions
- Sustainable and economic systems for the re-use of dairy effluent for forage production
- Improved grazing systems that enhance water quality.
- On-farm measurements of the water use efficiency of maize
- Efficient irrigation technologies to match soils and dairy farming systems
- Effect of mobilisation and transfer processes on nutrient exports from grazing systems.
- Exploring the effect of dairy farming practices on environmental health: towards a zone-based management framework - Patricia Hill
- Coordination of irrigation projects and management of Future Water
- Future Water (including Dairy Australia competitive bid; Joint with CSIRO, Rabobank & RDPs)
- Integrating irrigation and plant systems in Victoria's Dairy Industry
- National Effluent Management Guidelines
- Plant systems for efficient water use to meet the production requirements of irrigated dairy farms - Component 4 Water Use at initial irrigation of annual pastures

2) The Rural Water Use Efficiency (RWUE) project is a partnership between the Queensland Government and industry organisations representing the sugar industry,

dairy farmers, Cotton growers, nurseries and others to improve water management practices and efficient use of water (http://www.npird.gov.au/).

The program helps irrigators in each industry improve their on-farm management of natural resources, and reduce their off-farm impacts, particularly through efficient irrigation and management of nutrients. This will improve their productivity and help them meet the challenges of water reform.

To date, funding of $6.5 m over four years has been set aside to deliver the program. The program includes adoption/extension activities, on-farm trials, demonstrations and system assessments, and financial incentives to upgrade irrigation and effluent management systems.

3) The National Program for Sustainable Irrigation Program funds and manages research projects across Australia, working at the property level with farmers, at catchment level with policy makers and planners. It invests in research to improve the productivity and sustainability of irrigation in Australia (http://www.npird.gov.au/).

Some of the research projects include:

- Changing Irrigation Systems and Management in the Harvey Irrigation Area (DAW45)

The project was an on-farm trial comparing centre pivot and surface irrigation. It investigated on-farm water use efficiency and productivity, in addition to a system-wide water, energy and environmental issues.

- Irrigation Futures of the Goulburn Broken Catchment (VPI3) (Victoria)

The Goulburn Broken Irrigation Futures project used scenario planning with extensive stakeholder engagement to develop a vision and strategies for irrigated agriculture in the region over the next 30 years. It then provided a broad assessment of the scenario implications for business, the environment, communities and the key competencies of the region. A suite of regional response strategies were developed. The assessment process was then focussed to consider the implications for the strategic planning and operational activities of particular agencies dealing with irrigated agriculture, with each agency developing appropriate response strategies.

Barriers

Farmers need to be informed about the most efficient irrigation techniques suitable for their crops, and shown the benefits of irrigation management to maximise production and reduce runoff.

Erol (1999) identified the following barriers to adoption of adequate irrigation practices in the South West:

- Information provided for water and fertiliser use efficiency was not clear and concise
- Information needed to be in plain English
- Landholders needed more information about salinity causes and control
- Poor off-farm drainage prevented landholders taking further surface water and irrigation management actions
- Limited information on alternative farming practices
- Dairy farmers were still coming to grips with deregulation; many expressed uncertainty.

6.2.7 Retention Basin (Pond)

Retention basins or ponds are small artificial basins used for flood control and designed to remove pollutants from stormwater and can be used for water conservation and reuse.

The larger permanent pool of retention basins allows water to reside in the interval between storms, when further treatment occurs.

Benefits

- Can be designed to prevent off-site discharges of rainfall runoff, up to the design ARI event.
- Stormwater may be infiltrated to groundwater or used as a water source.
- Water conservation to collect water for irrigation or watering stocks

It is an effective sedimentation control system and provides high capture of coarse to medium silt-size solids conveyed in stormwater. Sediment removal efficiencies in retention basin range from 50 to 90%,

6.2.7.1 Technical Considerations

- Establish a recycling system to keep water on farm. Pump-back systems that return drain water back to the irrigation ditch reduce the amount of silt leaving the field because a portion of the water is being recycled and used over.
- Install flexible membrane linings in earthen ditches and/or reservoirs.
- Marsh plants around the perimeter of the pond provide the biological media to help remove nutrients and other dissolved constituents and trap small sediment and algae in the water column.

Monitoring and Maintenance

Maintenance would include:

- Algal bloom control
- Weed control
- Vector control

Cost Estimates

Taylor (2005) reported costs for ponds (sourced from limited data in Australia) ranging from \$2,000 ha^{-1} of catchment to \$30,000 ML^{-1} of pond volume, and \$60,000 ha^{-1} of pond area.

Barriers

- The treatment of water may be more expensive than treatment trenches, but is relatively easy to install and maintain.
- Requires co-operation of the farmer
- Requires land uptake, which can be expensive, unless benefits can be highlighted.

Research & Development

Water reuse: A demonstration site has been installed in the Peel–Harvey region (DoW, 2007) which stores drainage water offline and reuses it for irrigation. The reuse of water may contain high nutrient levels and should be researched in detail.

The Dirk Brook Demonstration Project used this BMP to capture and contain excessive irrigation water and summer runoff in a small earthen storage. This water was then re-used for irrigation.

6.2.8 Detention Basin

Detention basins are designed to temporarily store and slowly release run-off water. The water is released slowly and particulate pollution is settled in the detention basin. The main purpose of detention basins is to hold water to reduce peak flows. Detention of water in basin for a few hours will result lower efficiency in terms of removal of pollutants. If the detention time is increased to more than 24 hours, the basin is referred to as an extended detention basin and increased efficiency will result.

Figure 6-14 Detention Basin
(http://www.virtualcentre.org/en/dec/manure/img/Slide31.GIF)

Benefits

Fletcher *et al*., (2003) have stated that detention basins can control coarse sediments up to 95%, Nitrogen 20-60%, phosphorus 50–75% and heavy metals 40–70% dependent on particle size distribution, ionic charge, attachment to sediment (vs % soluble) and detention time.

Detention basins have benefits of:

- Water re-use

- Reduce both peak flow and volume from the catchment. Detention systems reduce the rate of off-site stormwater discharge by temporarily holding rainfall runoff (up to the design ARI event) and then releasing it slowly.
- Dry detention ponds detain the stormwater runoff for some minimum time (e.g., 72 hours) to allow particles and associated pollutants to settle.

Technical Considerations

- Extended dry detention basins are dry most of the time and able to store rainwater during wet conditions for up to 24 h; grassed surface and may have a low basal marsh.
- They reduce peak outflows in the post development scenario case to that of the predevelopment rates.
- Dry detention basins do not remove dissolved solids.
- Dry and extended detention basins provide some pollutant removal but the removal efficiency performance is highly variable.

Monitoring and Maintenance

Inspections should be conducted semi-annually and after significant storm events to identify potential problems early.

Biannual inspections for sediment accumulation, pest burrows, structural integrity of the outlet, and litter accumulation are typical. In parkland settings, maintenance plans should also address irrigation, nutrient and pest management issues. Accumulated sediment should be removed about every 5-7 years or when the accumulated sediment volume exceeds 10% of the basin volume. Sediment removal may not be required in the main detention area for as long as 20 years.

6.2.9 Infiltration Basin

Infiltration basins are detention areas constructed to allow infiltration to occur simultaneously with other treatment processes. Surface runoff is directed into shallow, landscaped depressions designed to incorporate many of the pollutant removal mechanisms that operate in forested ecosystems.

Benefits

- Can be sized to remove nutrients and dissolved constituents.
- Infiltration basins remove dissolved solids in the volume of infiltrated water.

- Infiltration basins can provide volume control and can effectively address the issues of increased frequency and duration of peak flows that are important in providing downstream channel protection.
- An infiltration basin intercepts and temporarily stores stormwater on its surface, where it eventually infiltrates into the ground. An infiltration basin often serves a small developed catchment, one with less than four hectares of tributary impervious surface.
- Properly operating infiltration basins can remove anywhere from zero to as high as 70 to 98% of the pollutants found in stormwater, depending on the constituent and site conditions. Also, when operating, infiltration basins can reduce the volume of stormwater runoff and virtually eliminate direct surface runoff for small storms (i.e., less than 6 mm to 13 mm of precipitation).
- Grass Swales-Removal rates exceeding 80% of TSS by grass swales are suggested by some researchers. Others suggest lower removal rates, on the order of 20 to 40% (UD&FCD, 1992). The higher rates suggested may be possible when soils have very high infiltration rates and very slow flow velocities occur (i.e., less than 0.15 m s^{-1}).
- In detention basins coarse sediments can be removed from 90–100% but it may pose a clogging risk. These systems should have pre-treatment to remove coarse sediment prior to entry to the filter media.
- Heavy metals removal in detention basins range from 50 to 95% dependent on state of particulate and its solubility (Fletcher, 2003).
- Litter removal in detention basins can be achieved more than 90%. Detention basins are expected to trap all gross pollutants, except during high-flow bypass (Fletcher, 2003).
- Soil with high sodicity is generally not considered to be suited for infiltration as a means of managing urban stormwater. Sodic soils (soils with a relatively high proportion of exchangeable sodium) result in increased soil dispersion and swelling of clays, which adversely impacts the soil structure and results in reduced infiltration, reduced hydraulic conductivity and the formation of surface crusts.
- Total Nitrogen removal in detention basins is 50–70%, Phosphorus removal is 40–80% and total suspended solids removal is 65–99% (Fletcher, 2003).

Technical Considerations

- An infiltration basin often serves a small developed catchment, one with less than four hectares of tributary impervious surface. When used to treat larger areas, they tend to clog. In addition, it is difficult to convey flow from a large area to a bioretention area.
- Grass swales appear to be best suited when terrain slopes are less than 3% to 4%, although some have suggested their use with terrain slopes as high as 6%.
- Soil with high sodicity (soils with a relatively high proportion of exchangeable sodium) is generally not considered to be suited for infiltration as a means of managing urban stormwater. Sodic soils cause increased soil dispersion and swelling of clays, which adversely impacts the soil structure and results in reduced infiltration, reduced hydraulic conductivity and the formation of surface crusts.
- Bioretention areas should usually be used on small sites (i.e., 5 acres or less). When used to treat larger areas, they tend to clog. In addition, it is difficult to convey flow from a large area to a bioretention area. Bioretention areas are best applied to relatively shallow slopes (usually about 5 percent). However, sufficient slope is needed at the site to ensure that water that enters the bioretention area can be connected with the storm drain system. These stormwater management practices are most often applied to parking lots or residential landscaped areas, which generally have shallow slopes.
- Percolation Trench-A percolation trench is a rock filled trench that temporarily stores stormwater and percolates it into the ground. A percolation trench typically serves small impervious tributary areas of two hectares or less.
- A soakaway is a type of ‘Infiltration Device’, a simple way of dispersing surface and storm water in situations where connection to the SW system is impractical or unwarranted. The basic principle is that of a 'reverse well' i.e. a 'hole-in-the-ground' that loses water rather than collecting water.

Monitoring and Maintenance

Infiltration basins perform better in well-drained permeable soils. Infiltration basins in areas of low permeability can clog within a couple years, and require more frequent inspections and maintenance.

The use and regular maintenance of pre-treatment BMPs will significantly minimize maintenance requirements for the basin. Spill response procedures and controls should be implemented to prevent spills from reaching the infiltration system.

Scarification or other disturbance should only be performed when there are actual signs of clogging or significant loss of infiltrative capacity, rather than on a routine basis. Always remove deposited sediments before scarification, and use a hand guided rotary tiller, if possible, or a disc harrow pulled by a light tractor.

Routine inspection is required to identify any surface ponding after the design infiltration period, which would indicate clogging/ blockage of the underlying aggregate or the base of the trench.

Routine inspection of inlet points to identify any areas of scour, litter build up, sediment accumulation or blockages.

Other maintenance activities include:

- Removal of accumulated sediment and clearing of blockages to inlets.
- Tilling of the infiltration surface, or removing the surface layer, if there is evidence of clogging.
- Maintaining the surface vegetation (if present).

Cost Estimates

URS (2003) estimated the unit rate for the construction of a 1m wide, 1m deep infiltration trench in Sydney as \$138 m^{-1}. This cost estimate included: excavation, installation of geofabric liner, installation of perforated pipe, installation of gravel layer, installation of filter layer, application of top-soil, application of grass seed, application of fertiliser and watering.

Taylor (2005) used limited Australian costing data for infiltration systems to estimate, the:

- Renewal / Adaptation cost 4.1% of total acquisition cost (per annum).
- Decommissioning costs 35% of total acquisition cost.

Cost estimates for infiltration trenches, based on eastern states examples, provide a construction cost range of \$46–\$138 per linear metre (based on a 1 m wide, 1 m deep trench)

Maintenance cost is expected to typically be in the range of ~5–20% of the construction cost.

6.2.10 Sedimentation Basins / Traps

Sedimentation basins or traps are basically a holding area which has considerably more capacity than the inflow into it. Traps cut down water velocity and allow silt to settle down.

Figure 6-15 Temporary silt trap with silt near an existing culvert (WML Consultants, 2005)

Benefits

Silt traps reduce water velocity and allow suspended solids to settle out, resulting in pollutants falling out as well. In some instances silt traps could result in significant reduction in pollutants entering the system. It may also be feasible for several owners to combine their efforts into one trap.

Silt traps reduce the amount of silt leaving farmers fields and the amount of silt entering the waterways, estuaries and sea is reduced by 30-50%. Coarse sediments are reduced up to 10–25%, total suspended solids 0–10% and litter 10–30% depending on hydraulic characteristics and this reduction will be higher during low flow (Fletcher *et al*., 2003)

Removal efficiencies of 90% of solids greater than 900 microns have been reported for Gross pollutant traps (GPT) (Wong, 1996).

Technical Considerations

Gross pollutant traps (GPT) can be used in the waterway flow to remove litter and other relatively large suspended materials (Peel Development Commission, 2006).

Silt traps may be feasible in areas where water can be detained prior to discharge into larger drains. They work by cutting down water velocity and allowing silt to settle out (WML Consultants, 2005).

The velocity of drain water should be below the 2 m s^{-1} speed at which soil particles are not picked up and put into suspension by the speed of the water. The faster the water flows, the more silt it will carry in suspension. Once the silt is in suspension, and the drain water is muddy, it becomes almost impossible to improve the situation until that muddy water has left the field. If you keep the drain water moving slow from the very start, it becomes much simpler to manage.

Monitoring and Maintenance

Regular inspection and cleaning is essential to maintain the performance of the trapping devices and prevent them from blockages or releasing pollutants. Poorly maintained devices can increase the risk of upstream flooding

The land manager should have a site specific maintenance plan, providing guidance on a suitable inspection regime, maintenance practices (including guidelines on the equipment to be used, health and safety procedures, waste disposal arrangements, etc.) and responsibilities. These plans should be prepared in consultation with relevant maintenance personnel. Health and safety procedures need to address handling trapped litter that may contain needles and other sharp objects.

Cost Estimates

Costs of various litter and sedimentation management systems are variable and should be assessed on individual cases Taylor (2005).

Taylor (2005) used Australian costing data to estimate that for sediment basins and ponds:

- Renewal / Adaptation cost 1.4% of total acquisition cost (per annum).
- Annual maintenance costs presented in Taylor (2005) (cited as Weber 2001 and 2002) typically range in the order of 7 to 30% of the capital cost.
- Decommissioning costs 38% of total acquisition cost.

Weber (2001 and 2002) reported in Taylor and Wong (2002): Typical annual maintenance cost 6% of construction cost. Also, typical construction cost $50,000 and typical annual maintenance cost $2,800.

Lloyd *et al*., (2002) developed some BMP size / cost relationships for litter and sediment traps (combined):

- Construction cost ($) 13,703 x (Catchment area in ha).
- Annual maintenance cost ($) 311.67 x (annual volume of material removed from the trap in m^3).

Taylor (2005) used Australian GPT costing data to estimate that for GPTs when considered as a

group, the:

- Cost of defining the need for the BMP3 (N) 4.8% of total construction (TC) cost.
- Total design cost (DC) 11% of TC.
- Total construction cost (TC) 94% of total acquisition cost (TAC), where TAC N + DC +TC.
- Typical annual maintenance costs (TAM) 7.6% of total acquisition cost (TAC).
- Renewal / Adaptation costs 0.71% of total acquisition cost (per annum).
- Decommissioning costs 16% of total acquisition cost.

6.2.11 Spoil Management

Spoil Management is the re-distribution of the dredged material accumulated as deposits on the banks of drains and channels to re-establish the natural flow of water and maintain the hydraulic and environmental functions of the waterway.

Benefits

- Reducing drainage maintenance requirements
- Reduces in-drain erosion and sediments entering the drainage system.

Technical Considerations

- If spoil is not left in the form of levee it will end up in stream.
- Placing spoil well clear of excavation creates a berm allowing machinery for channel maintenance.

- Spoil banks should be shaped so that as much runoff as possible flows to the out sides of the levees.
- Spoil banks heights should always include an additional 0.2 m for freeboard, to allow for a surcharge during peak flows.
- The optimum side-slope angle to prevent slumping spoil is shaped into a bank with side slope ratios 3:1 (horizontal: vertical) towards drain and 4:1 away from drain.
- In straight channels spoil banks can be placed some distance away from the drain channel but in meandering areas, placement would ideally be outside the meander belt.

Monitoring and Maintenance

- One of the standard maintenance practices is to dredge the base of the drainage channel to remove vegetation and sediment build-ups. This tends to increase the depth and width of the channel (English, 1994).
- The capacity of the drainage channel is enhanced due to the practice of the excavated sediments being placed alongside the drainage channels. The spoil banks act like levees and further increase the system's capacity to convey flows. Greater depth may also increase the erosive capacity of the drain in high flows facilitating the re-suspension and movement of bed loads.
- In some cases, the nutrient content of sediment removed from waterway beds may be high. It is suggested that new spoil generated from maintenance be removed away from the drainage corridor and other areas where it can quickly re-enter the drainage system.
- Regular visual inspection of drains and trenches should be conducted to check that the spoils are not being eroded in the waterway.
- Placing spoil well clear of excavation creates a berm allowing machinery for channel maintenance.
- Weeds killed by periodic chemical sprays should be removed from the drain so that the drain section is kept clean.

Cost Estimates

The cost consists of hiring a front end loader between \$250 and \$300 $hour^{-1}$.

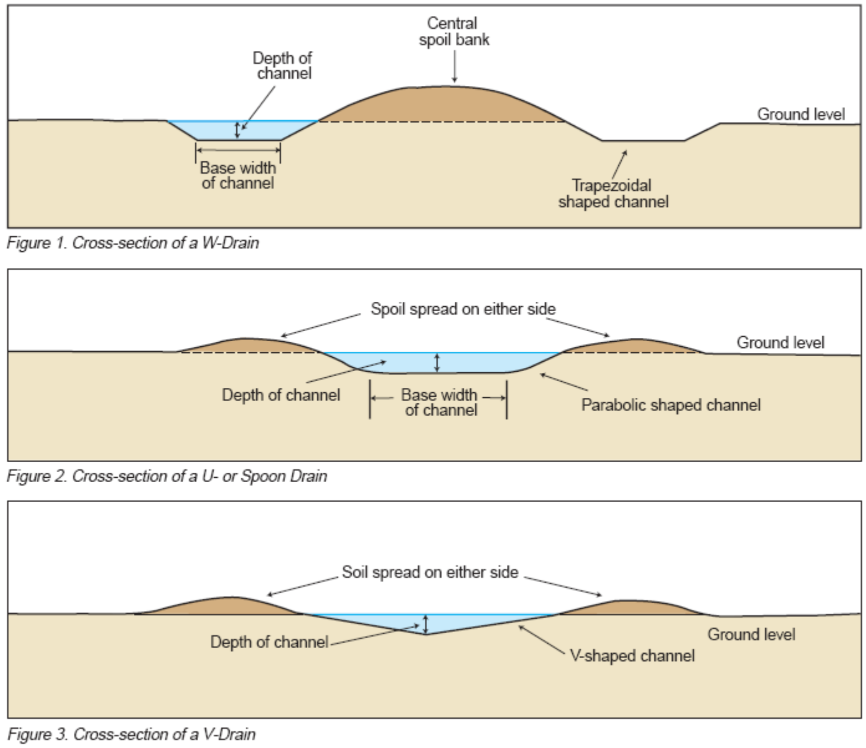


Figure 6-16 Spoil Management on Different Drain Types (Dept. of Agri., 2003)

6.2.12 Constructed Wetlands

Stormwater often carries litter and sediment into rivers, creeks and bays. Contaminants and nutrients are attached to the sediment particles.

The use of wetlands as stormwater quality enhancing facilities is an emerging technology. Wetlands can be used as source controls or as follow-up treatment devices. A wetland basin, in essence, is another form of an extended detention basin or a retention pond. As a result, all of the constituent removal processes listed for an extended detention basin and a retention pond should also apply to a wetland basin. A wetland channel is similar to a grass-lined channel, except it is designed to develop wetland growth on its bottom and is typified by a flat longitudinal slope, wide bottom and slow flow velocities during the two-year and smaller storm runoff events. A wetland channel, to a smaller degree and depending on specific site conditions and design, probably has many of the constituent removal characteristics of a wetland basin.

Wetlands also help to trap and utilise nutrients such as phosphorous and nitrogen, converting them to valuable food to sustain birds, fish and frogs. Wetlands act as storage basins for floodwater providing slow water release.

Hydraulic efficiency of wetlands and characteristics of the target pollutants (e.g., particle size distribution and contaminant type) largely influence their differences in performance.

Benefits

- Wetlands provide storage, allow sediments to be trapped, provide an eco-system that 'clean up' collected water, while allowing a degree of infiltration and providing a more attractive and bio-diverse environment. Roles of wetland vegetation is the promotion of enhance sedimentation processes. These processes involve the facilitation of uniform flow conditions within the wetland and provision of a medium for small-particle adhesion. The pre-dominantly two-dimensional flow pattern through dense vegetation during the filling and draining cycle of the system further enhanced sedimentation processes promoted by the presence of vegetation in the system.
- Wetlands provide habitat for fish and other animals that support tourism, hunting and fishing. Wetlands also minimize the effects of erosion and act as a filter, preventing upland pollution from entering the water as stormwater runoff.
- Wetlands slow the flow of water, reduce the amount of sediment being carried and enable biological processes, sunlight and time to help purify the water. The wetlands are designed to act as a filter, with thousands of aquatic and semi-aquatic plants in various water depths removing nitrogen and other pollutants. They act as sponges, storing and soaking up excess water; and filters, cleaning water as it flows through.
- Wetlands provide many benefits, including food and habitat for fish and wildlife; flood protection; shoreline erosion control; natural products for human use; water quality improvement; and opportunities for recreation, education, and research. More than 75% of commercial fish species require estuarine wetlands to complete part of their lifecycle. Many local and migratory birds also utilise wetlands as breeding and roosting sites.
- Some landholders have installed secondary water control structures at the edge of their back swamps to allow water storage in wetlands at the end of the wet season. This not only helps to restore the beneficial capacities of wetlands, but also promotes maximum vegetation growth in the summer as a source of fodder for stock.

Technical Considerations

Wetland sites are generally chosen next to rivers and creeks that require water quality treatment, and in conjunction with other measures such as litter traps. If drainage is poor or very poor in a place and if the water table is at or near the surface for a considerable time, then there are chances that it can support a wetland habitat.

In agricultural areas, small-scale wetlands or storm drainage retrofits could be installed at the end of the surface or tile drainage systems. These wetlands are formed by berming an area adjacent to a stream and forming a small detention basin or holding pond that intercepts surface and tile drainage water before it enters a stream.

Good wetland restoration potential if the soil is:

- Seasonally flooded
- Has a very high water table (0.3 m of ground surface)
- Poorly drained
- Soggy ground or pools of water
- Small (flowing or not) stream channels on site (less than one foot deep)
- In the floodplain
- Poor wetland restoration potential if the land is:
- Well-drained
- located on ridge-tops
- Sandy or gravely.
- Forested
- Woody vegetation mostly over 1.5 m tall
- Indicators of good wetland suitability:
- Stable wetlands in adjacent land
- Close proximity to a stream
- Flat terrain or gently sloping towards the site
- Neighbouring land used for agriculture, recreation, aesthetic qualities, or wildlife
- Indicators of potential problems for wetland suitability:
- No nearby wetlands or visible water source
- Land slopes down away from site, not allowing for water retention
- Adjacent structures that would easily flood with the wetland
- Sites most likely to be successful for wetlands restoration or creation are:

- Former wetlands that have been drained for agricultural or other purposes
- Former wetlands now in a degraded condition
- Disturbed areas such as construction sites
- Areas that are accessible to earthmoving equipment
- Open, inbuilt areas or lawns
- Ponds
- Sites most likely to be unsuitable for wetlands restoration or creation are:
- Upland forested areas
- Areas identified as important habitat for rare, threatened, and endangered species
- Areas with moderate to steep slopes
- Sites with structures that would definitely flood if the area was restored to wetland"
- Drainage of wetlands removes their filtering capacities and prevents the improvement of water quality before water moves downstream. It also prevents the steady release of nutrient laden water containing micro-organisms necessary to support the estuarine food web. Straw Bales should be installed around areas requiring protection to form a temporary containment. Straw bales work much like silt fencing and can be used to form a barrier or redirect water. Unlike silt fence, straw bales do not allow water to flow through freely, thus they are used where detention, not just filtration, is necessary.

Wetlands should not be subjected to the following activities:

- Drainage for agriculture, horticulture and forestry.
- Extraction of groundwater
- Grazing and watering of stock.
- Use of wetlands as evaporation basins for highly saline irrigation water.

Wet lands can remove 95% of litter subject to appropriate hydrologic control. Litter and coarse organic matter should ideally be removed in an aerobic environment prior to the wetland, to reduce potential impacts on biological oxygen demand. Fletcher *et al*., (2003) estimate that total suspended solids up to 65–95%, nitrogen 40–80%, phosphorus 60–85%, coarse sediment 95% and heavy metals 55–95% are removed in wet lands.

Monitoring and Maintenance

Wetlands should be managed and protected against:

- Inundation
- Salinisation
- Weed invasion
- Wildfires
- Discharge of industrial effluents and petroleum products.

Inspections should occur every 1 - 6 months depending on the size and complexity of the system. More detailed site specific maintenance schedules should be developed for major constructed wetland systems and include a brief overview of the operation of the system and key aspects to be checked during each inspection.

Typical maintenance of constructed wetlands involves:

- De-silting the inlet zone following the construction/ building period
- Routine inspection of the wetland to identify any damage to vegetation, scouring, formation of isolated pools, litter and debris build up or excessive mosquitoes
- Routine inspection of inlet and outlet points to identify any areas of scour, litter build up and blockages
- Removal of litter and debris
- Removal and management of invasive weeds
- Repair to wetland profile to prevent the formation of isolated pools
- Periodic (usually every 5 years) draining and de-silting of the inlet pond
- Regular watering of littoral vegetation during plant establishment
- Water level control during plant establishment
- Replacement of plants that have died (from any cause) with plants of equivalent size and species as detailed in the planting schedule
- Vegetation pest monitoring and control.

Cost Estimates

Weber (2002) cited in Taylor and Wong (2002) quoted estimates ranging from approximately \$500,000 to \$750,000 per wetland hectare based on eastern states examples.

Barriers

Constructed wetlands require significant areas of land, so decisions about the best use of land will need to be made. There must also be adequate room to allow personnel access to clean and maintain a wetland.

Engaging local community groups in management of wetlands, e.g. to undertake removal of weed species - also engage community in the planning process to identify their 'values' and aspirations with regards to the wetland.

Government funding for formal wetland inventory and evaluation is currently limited. Mapping of wetland habitats is also limited, especially in areas that fall within private estates, which represents a gap in our understanding in the values of the area.

Research & Development

The Marshall's Constructed Wetland in Torbay Catchment was constructed in January 2001 on an area of low-lying unproductive pasture. It captures and treats sediment and nutrient - rich runoff from a catchment area of 150 hectares. This wetland was designed to mimic the sediment and nutrient removal processes of natural wetlands. Catchment run-off flows into the sediment pond. It is designed to slow flow rates enough for larger sediment particles to drop out. The water then flows through the perforated rock bund to the next "bio-filter" pond (http://www.torbay.scric.org/pub/restplan/rpb2t3.html).

The Tom Bateman Reserve Constructed Wetland project by the City of Gosnells delivered a variety of social, environmental and economic benefits. The wetland development intercepts two drainage systems feeding pollutants into the nearby Canning River and a mix of seasonal and permanent waterbodies. Using the concept of Living Streams, the wetland system is designed to trap pollutants from the nearby Canning Vale Industrial Estate and use planted vegetation to remove contaminants before they are released back into the Canning River.

Constructed wetlands have been used in a small scale urban setting in the Rainforest Reserve, Byford. The site was a previously cleared local discharge zone within the foothills.

6.2.13 Waterway Restoration / Living Streams

Streams, rivers, water bodies and wetlands are important for nature conservation and local ecology as well as local waterway usage and floodwater discharge. The normal patterns of flow and the natural water balance of the existing ecosystems may be altered due to local or upstream conditions that adversely impact the functional integrity of the structure. All landholders have a duty of care to the land and to other landholders within their catchment. Environmental considerations will impact upon the ability to construct or restore waterways to function properly and to provide environmental benefits to its surroundings.

Benefits

- Reduces soil loss and downstream channel sedimentation.
- Adequately restored drains take excess water from low-lying areas to the coast either through adjacent estuarine or ocean outlets. Controlling drainage in the lower coastal plain is the most effective BMP for reducing nitrogen losses into streams and ditches.
- Aesthetic improvements, Habitat enhancement, Safety
- Controls water logging or seasonal / permanent inundation of land, thereby protecting field crops.
- Waterway restoration stops deterioration of assets such as bridges, culverts and connecting pipes.
- To prevent an excessive accumulation of soluble salts in the soil that might be detrimental to plant growth.
- Waterway restoration will reduce soil loss and downstream channel sedimentation. Channel side slopes and berms are exposed to raindrop impacts and runoff generation inside spoil banks and berms in episodic rainfall events. Erosion of deep channel side slopes result in accumulation of sediments at the base of the channel which reduce the hydraulic capacity of the channel.

Technical Considerations

- Drainage ways and their associated vegetation should be retained in their natural state. In particular, water flow in streams, creeks and natural drainage swales should not be altered by changing the channel shape and surface (e.g. by constructing a concrete culvert) or by damming. Existing elements of the drainage system, such as natural channels, wetlands and riparian vegetation, should be preserved. If possible, drains should be designed to follow the existing drainage lines in well defined depressions.

- The impact of saline and or acidic groundwater discharging into natural watercourses, lakes or wetlands should be a consideration in determining the acceptability of a waterways design, by way of varying channel depth, outflow or use of design considerations such as flow gates.
- Installation of simple rock riffles, drop structures and grassed field borders should be used in areas where erosion has or is likely to occur. Open ditches should be flat bottomed rather than V-shaped to prevent scouring.
- Channel features such as pools, riffles, steps and undercut banks provide diversity of habitat, oxygenation and cover. For these reasons natural resource managers increasingly use natural channel design to restore impaired streams.
- Re-contour banks, riffles, meandering, revegetation of banks to widen the stream channel and floodplain, creating wetlands that would store excess water during flooding and act as habitat for fish and wildlife. Add log structures and spawning gravel to the stream channel to improve fish habitat along with an extensive revegetation of native plantings.
- Add log structures and spawning gravel to the stream channel to improve fish habitat along with an extensive revegetation of native plantings.
- Drains range from 1 m to 10 adjacent to the drain on one or both sides. Angle of side slope (batter) is a critical factor for managing erosion and sedimentation within the channel. The optimum side-slope angle to prevent erosion for drains over 1.2 m depth ranges from 1:1 in clays to 3:1 in sandy soils. Slumping can be minimised in cohesive clayey sub-soils by ensuring that side-batters are between 1.5:1 and 3:1 depending on soil type.
- As a rule, the flatter batter slopes are required in coarser textured soils than in the heavier fine textured soils. Slope and hydraulic gradient are important considerations when installing deep drains. On broad Wheatbelt valleys where hydraulic gradients are typically very low, a drain may need to be more than 2 km long to have sufficient fall for outflow of groundwater into a receiving waterway or containment structure.

- Spacing depends on the hydraulic conductivity of soils, rainfall and topography. In flat areas drains can be parallel and in sloping areas drains are constructed parallel to contour lines.
- Care must be taken to ensure that poor quality discharge water does not affect land and water supplies downstream.
- Channel side slopes and berms, when exposed to episodic rainfall events and runoff generation result in erosion and sedimentation at the base of the channel, reducing its hydraulic capacity. Additional saline and acidic water with heavy metals and agricultural chemicals may discharge from an upstream source.
- The water quality of the drains depends upon the various activities that occur within the catchment area of the drainage system. Outputs over the property boundaries depend primarily upon the various practices of the landowner. If best agricultural practices are not employed in agriculture production, then various nutrients (phosphorus and nitrogen), pesticides and soil erosion products (sediment) can escape from the property and enter the drainage system.
- Capacities for open collector drains should be sufficient to carry normal flows of groundwater, irrigation surface waste, estimated storm flow, and the quantities delivered to the collector drains by tile and deep open drains. The minimum capacity of surface drain channels should be 0.08 to 0.14 m^3 s^{-1}. Design culverts to expected volumes of flow ARI 20 and 50 years.
- General rules to follow for constructions of mains and sub-mains is to follow the general direction of natural drainage ways, construct straight drains with gradual curves, use the available grade to best advantage and avoid the unstable soils. Slope and geometry of the site, proximity and classification of bedrock beneath the bottom, and the drainage site characteristics (soils, geology, and gradient of slopes) will be assessed to establish the potential for effective drainage. Design guidelines are required for drainage projects varying from farm scale to catchment and regional scale.
- Design culverts to expected volumes of flow for ARI 100 years.
- Bankfull geometry for channel design. The deeper a drain, the greater is the width of adjacent land affected by the drawdown of the groundwater. The drainage system should not be ‘over-designed’ so excessive earthworks and bank armouring are needed. Depth to watertable, seepage rate into channel and road crossings are additional parameters to be considered for the designing and planning of channel

system. Deep channels tapped into saline and acid groundwater, allowing it to be flushed into rivers and streams. Safe channel effluent disposal into evaporation basins, lakes and streams should be the part of channel planning.

- Hydrogeology, topography and catchment urbanisation need to be considered.
- Increase the drain length by not straightening existing waterways, drains or creeks. This reduces the steepness of the drainage system and stops water running off too quickly, thus minimising erosion.
- Surface water management to manage the salinity, flood, and water logging problems in southwest of Western Australia. Design surfaced catchments for storage of runoff into farm dams, roofed rainwater harvesting and storage in rain water tanks for human and livestock consumption. Install banks, spoon and W-drains, reverse-bank seepage interceptor and shallow and deep drainage channels for managing surface and groundwater. Interceptor/Grade banks should be constructed on a grade that ensures adequate flow without causing scouring of the channel. There is a range of design options but generally they are constructed to intercept both surface water run-off and sub-surface flow in duplex profile soils on sloping landscape positions. Spoon or W-drains are effective in removing ponded water. The drains are located in the lower landscape where waterways would be ineffective because of low gradients and are used to intercept overland flow in low-lying areas. Detention storage (i.e. dams) can be used to retain flows from saline seeps or from groundwater pumping during periods of low streamflow (e.g. summer) or low rainfall. Water contained in the storage can then be released during high rainfall events or during periods of high streamflow (e.g. winter). In this way saline effluent can be disposed of into natural drainage lines with limited impact on the environment.
- Install surface and/or subsurface drains or groundwater bores and manage drainage waters. Use and manage groundwater in conjunction with surface water. Concentrate production on the lowest salinity soils. Do not fallow during wet seasons. Fence off and vegetate recharge and discharge areas. Plant salt tolerant pastures. Establish deep-rooted pastures or revegetate with suitable species.
- Characterization of sediment-transport conditions at different ARI flows.
- As a rule, the flatter batter slopes are required in coarser textured soils than in the heavier fine textured soils. Slope and hydraulic gradient are also important considerations when installing deep drains. A minimum grade of 0.01 to 0.005% is

desirable for open drains and 0.15 to 0.2% for tile drains or slotted pipe drains. Filters are required when using slotted tube drains. A gravel filter around the pipe is required if the water bearing material is fine sand or silt. Woven nylon systems should not be used when groundwater contains high levels of iron.

- Restore stability to disturbed streams by rebuilding natural stream characteristics, including a properly sized bankfull channel, adequate floodplain width, meanders, riffles and pools.
- Plant native trees and shrubs as part of a comprehensive native riparian landscaping plan.
- The drainage proposal must show how the drainage water will be disposed of. Disposing of good quality drainage water poses few problems. However, care must be taken to ensure that poor quality discharge water does not affect land and water supplies downstream. In these cases, the design must prevent any adverse effects. Sediment traps may be needed or collecting and reusing the water on site may be a better alternative.
- Where drainage water is derived from only surface drainage or tail water sources, the main question is whether or not the water contains applied and persistent pesticides. In areas where strong environmental safeguards exist and pesticide container label restrictions are followed, there is little risk associated with the re-use of surface runoff or tail water drainage water. Rice field drainage water accounts for a very large percentage of the water supply for managed natural wetlands in the Sacramento Valley in California and is generally safe for re-use. The re-use of subsurface saline agricultural drainage water for wetland management poses substantial challenges and can generate problems which could result in wildlife losses and habitat reductions. In WA for Water Storage/Reuse - a great example of this is the Dirk Brook project, but also the LCC have a demo site where this has been installed on paddock level drainage.
- The expanded drainage network has increased the generation and export of acidity from acid sulphate soils. Drainage systems can rapidly transfer acidity and deoxygenated water from back swamp areas to creeks and estuaries after rain.
- Acid Sulphate Soils can generate large amounts of acidity, iron and aluminium when they are exposed to air, either by excavation or by lowering the watertable via drainage or drought.

- Smaller drains tend to require more frequent maintenance than larger ones. Consider the effect of saline effluents on existing vegetation, especially in flora and fauna reserve and National Parks.
- Catchment hydro modification, canalisation, loss of riparian vegetation, floodplain restrictions and changes in hydrology have altered the dimension, pattern, and profile, and thereby the function, and habitat of many coastal streams.
- Because of the commercial value of the drainage areas very little native vegetation was left in the drainage districts.
- Stream salinisation is a major problem in south-west WA. Restricted drainage is a factor that usually contributes to the salinisation of soils and may involve the presence of a high ground-water table or low permeability of the soil.
- Most drains are steep sided due to lower construction costs, width of drainage and road reserves and the commercial value of the land in the district.
- Perhaps the most common soil management problem in relation to drainage is compaction. Soil compaction prevents water entering the drainage system. It is often caused by heavy machinery operating when soils are wet and most frequently occurs on headlands, gateways and heavily trafficked areas. Use of low ground pressure tyres should also be considered. Heavier textured clay and clay loam soils need good stock management to prevent compaction by cattle and sheep. This may mean standing cows off the paddock during rain after they have eaten the grass on offer. If compaction has resulted, deep ripping during summer may be necessary to re-establish drainage paths.

Cost Estimates

Surface drainage systems require the least initial investment and are often more effective in ‘tight’ clay-textured subsoils; however, maintenance is high and ditch space is non-productive. Quoted prices are from Farm Weekly Budget Guide, (Farm Weekly, Fairfax Media, 2006).

- Leveed deep drains (LDD) are drains that only handle subsurface flows and are completely surrounded with spoil to form a levee to exclude surface water. Prices below are for construction with 45 tonne excavator fitted with rippers, specially designed buckets and lasers to gain accurate grades.

LDD 1.8 metre deep with 0.5:1 batter $4,500 per km

LDD 2.2 metre deep with 0.5:1 batter $5,000 per km

LDD 2.5 metre deep with 0.5:1 batter $5,500 per km

LDD 3.0 metre deep with 0.5:1 batter $8,000 per km

Prices will vary if large amounts of hard rock are encountered.

- Shallow channels are constructed to better handle over land flow spoil stacked so as not to interfere with flow, normally on alternate sides and 1.5 metres from edge of channel.

SC 0.5 metre deep with 0.75:1 batter 3 metres wide $2,000 per km

SC 1.0 metre deep with 0.75:1 batter 3 metres wide $3,500 per km

SC 0.5 metre deep with 0.75:1 batter 5 metres wide $3,500 per km

SC 1.0 metre deep with 0.75:1 batter 5 metres wide $5,000 per km

Prices are for construction with 45 tonne or 30 tonne excavators with specially designed buckets and lasers to gain accurate grades.

- Drain clean-out

Silt depth 0.3 metres $1,000

Silt depth 0.6 metres $1,600

Silt depth 0.9 metres $3,000

Prices are for 30 tonne excavator fitted with clean-out bucket.

The following table is taken from Chapter 9 - Stormwater Management Manual for Western Australia: Structural Controls

Monitoring and Maintenance

Effective waterway management is important for preventing environmental problems. Sediments, nutrients (fertilisers), herbicides, pesticides, organic wastes or pollutants washed into the drains flow into the stream and impact on water quality downstream. Improved drainage can lead to flooding elsewhere if more water enters the waterway during times of high rainfall. If the receiving waterway is unable to accommodate the extra water, flooding, erosion and habitat disturbance downstream may result.

Waterways must be regularly inspected and maintained to achieve long-term effectiveness in performance for removing water.

Table 6-8 Costs of Some Waterway Restoration Projects in WA
(http://www.csiro.au/files/files/p350.pdf)

Project	Scope of Work	Total Capital Cost ($)	Unit Cost ($/m^2)
Baigup Reserve, City of Bayswater	Weed control, revegetation, signage and boardwalks for an area of approx 20 ha adjacent to Swan River.	500 000	2.50
Paterson St Drain City of Bayswater	Restoration of 100 m section of Water Corporation steep sided trapezoidal drain. Works included weed control, revegetation and earthworks to lessen bank slope and introduce meanders. Cost includes professional fees of landscape design and survey. Approx total area : 0.15 ha	26 000	17.30
Jane Brook Shire of Mundaring	Weed control and revegetation of Falls Park and Brookside Park Parkerville. Streambed erosion occurring due to flows from upstream urban development. Approx total area of project : 5 ha	106 000	2.12
Avon River Shire of Toodyay	Weed control and revegetation of 1 ha area at Duidgee Park Toodyay. Approx area of project : 0.1 ha	4 600	4.60
Mahogany Creek Shire of Mundaring	Weed control and revegetation of 0.06 ha area of Mahogany Creek in Hovea.	2 400	4.00

Source: Water and Rivers Commission (1999)

Performance criteria can include parameters such as suspended sediment load and rate of lateral channel migration.

Inspection should be done for the following:

- Stock access:

If stock have broken, and gone through, fences the waterway may get damaged.

- Water logging problems, especially after rainy days.

Poor crop establishment and growth patches of excessive weed growth indicate water logging. For initial investigation, take a spade or backhoe or an auger and dig a series of small pits or holes up to 1-3 metre deep in and around wet areas. Test pits, holes or drilling determines the hydraulic conductivity and quality of sub-surface flow. Diagnosis is best done when soils are wet. Signs of water logging to look for on the soil surface include whether there is ponding, pugging by stock and rutting by machinery.

- Flooding.

If the receiving waterway is unable to accommodate the extra water, flooding, erosion and habitat disturbance downstream may result.

- Nutrient levels

Increased nutrient levels in the waters result in algal blooms. Moderately high algal productivity will generally exist with TP in the range of 20 to 50 μg L^{-1} (Gilliom, 1984 and Simpson and Reckhow, 1979). TN to TP ratios should be maintained above 10:1 to prevent blue green algae.

Maintenance work includes the following:

- Nutrient Control

Outputs over the property boundaries depend primarily upon the various practices of the landowner. If best agricultural practices are not employed in agriculture production, then various nutrients (phosphorus and nitrogen), pesticides and soil erosion products (sediment) can escape from the property and enter the drainage system.

- Weed Control

A carefully planned weed control program should be implemented annually. Using the wrong weed control methods could be expensive and make the drains ineffective. If using chemical sprays, select the right chemicals so that the weeds are controlled without killing animals, such as frogs and fish that may live in the drain.

Weeds should be sprayed in arterial ditches before winter to allow water to flow away quickly and reduce the rate of silting. Spraying is considerably cheaper than using an excavator. Only appropriately registered chemicals should be used.

- Channel banks

Most drains are steep sided due to lower construction costs, width of drainage and road reserves and the commercial value of the land in the district. Erosion of deep drains side slopes will result in accumulation of sediments at the base of the drain. Silting of the drain invert and subsequent growth of reeds reduces the drain water carrying capacity and impedes water flow. The side slopes of the open drain, particularly the sides above water surface should be planted to grass and fertilised every 2 years.

- Soil Compaction

Soil compaction prevents water entering the drainage system. Heavy textured clay and clay loam soils need good stock management to prevent compaction by cattle and sheep. If compaction has resulted, deep ripping during summer may be necessary to re-establish drainage paths. Heavy operating machinery on wet soils will also cause soil compaction. Use of low ground pressure tyres should also be considered.

- Water Table Management

Water table management requires periodic monitoring of the water table at the midpoint between drain laterals or ditches. It is best done by the farmer. One observation well per field is the minimum recommended. For a given soil and drain spacing, the frequency of observation and adjustment of the control structure depend mainly on the weather and crop development stage. For example, when crops are in their early stages of development, a shallow water table may impede proper root development, and this could make the crop more susceptible to drought later in the year. Research by Madramootoo *et al*., (1993 and 1995) indicates that water table levels between 0.50 m and 0.75 m from the soil surface are appropriate for most crops.

The primary need for subsurface drainage is during the planting and harvesting s when excess water may limit the ability to operate heavy equipment. Drainage may not be needed in other portions of the season. A control structure can be placed in the drainage outlet or along a sub-main to block the flow of water. The discharge can be controlled during the growing season and at other times.

Research and Development

Several community groups and schools are working through Ribbons of Blue/ Waterwatch WA, with the help the Department of Environment and Conservation and the Department of Water to increase environmental awareness and provide assistance to communities to take action to improve the environment (http://www.peel-harvey.org.au/content/cci_projects/cci_p4_bpap.asp).

Some of the case studies are:

- Avon Community Group members prepared a riparian revegetation trial site for the restoration of Phillips Brook, to combat the problem of bank erosion and consequent high sediment levels. Weed control measures were implemented and the group also planted trees native to the region. Log walling has been constructed with tree branches and logs secured to sections of the bank to dissipate stream energy and protect the newly revegetated embankments. Several rock riffle structures have been created to arrest the erosive power of the stream flow, reducing scouring and the transportation of sediment downstream.

- A restoration project began in 2003 on a weed-infested drain in the centre of Bridgetown. Blackwood Waterwatch joined the Shire of Bridgetown-Greenbushes, the Department of Environment and the 'Friends of the Geegeelup Brook' to provide support and advice on the project.
- Four rock riffles were constructed, creating deep pools. The channel was widened and reclaimed from the Kikuyu grass, which had been smothering the brook.
- The Boyup Brook Billabong Rehabilitation Project aimed to restore the environmental values and the ecological functioning and biodiversity of the existing native flora and fauna of the Brook, pool and Shire reserve. The area of the project covers 18 ha of both native vegetation and weed-infested areas. The early stages of the project included assessing the site, identifying which were native plants and which were weeds, and removing weeds from the remaining riparian vegetation along the brook.

During the rehabilitation stages of the project, Boyup Brook students assisted in growing and planting over 3,000 seedlings in 2005 consisting entirely of local species grown at the community landcare nursery using local seed stock collected from the project area.

6.2.14 In-stream Structures

This BMP involves constructing hurdles, drops and weirs in the upper reaches of the waterway to reduce flows and transport loads. This may involve drain modifications such as recreating meanders, providing riffles and laying back sides slopes.

Figure 6-17 Major drop structure (WML Consultants, 2005)

Example of In-Stream Structures

- Denitrification trench is a technique used to treat plumes of nitrate in groundwater under anaerobic conditions. High concentrations of nitrate from inorganic fertilisers, septic tanks, dairies, feedlots and animal holding areas contaminate groundwater and cause environmental harm (Fahrner, 2002). Denitrification trenches are constructed down gradient of these areas to intercept groundwater and reduce the nitrate concentration. The method involves constructing a trench with varying dimensions, the soil excavated is mixed with a carbon source, usually pine sawdust or woodchip mulch, and then returned to the trench. Other material suggested includes coconut husks and a hardwood material such as jarrah sawdust. The carbon material works as a catalyst to increase the activity of denitrifying bacteria in the soil and speed up the rate of denitrification of the groundwater passing through the trench (Schipper *et al*, 2001).
- Provide saw dust trenches to intercept ground water flows to the drainage system. The provision of these trenches will remove significant amounts of nitrate from ground water. Identified “hot spots” such as feed lots, dairies and pig pens where hydraulic head or ground conditions are such that the effluent is forced to flow through the trench.

• Root Wads (root mass or root ball of a tree, including a portion of the trunk) armour a stream bank by deflecting stream flows away from the bank. They also support the stream bank structurally, provide habitat for fish and other aquatic animals and supply food for aquatic insects.

• Snags, Logs and Rocks

Snags are fallen branches and washed-in shrubs. Protruding snags provide safe perching and roosting sites for birds. Aquatic plants provide food and dissolved oxygen for aquatic species. Habitat improvement structures include check dams, boulder placement, channel constrictors, covers and shelters, migration barriers, gravel traps, and bank covers.

Figure 6-18 Root Wad Placed on Outside of Meander Bend
(http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_contents.html)

• J-Hook Vane

A J-hook vane is an upstream pointing line of rocks that originates at one bank and terminates somewhere in the middle of the stream. The most upstream portion of the structure bends back on itself, like a ‘J’ curving into the middle of the channel. This bent portion serves to concentrate flow and scour out a pool while the length closer to the shore deflects flow away from the bank. The cross vane and J hook should be oriented upstream at an angle of 20-30 degrees with the stream bank.

The structures are highest near the bank, to provide stream bank protection and these structures are built with rocks with sizes heavier than 1 to 2 tonnes. Footer rocks should be placed above and below the structure to help hold it in place.

Figure 6-19 J-Hook Vane
(http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_contents.html)

- Cross Vanes

A cross a vane is made up of a set of upstream angled lines of boulders, connected by a section of smaller rocks upstream. While water usually covers the shorter section during normal flows, the taller sections deflect flow away from the banks of the stream. Flow is diverted over the rock walls and concentrated down the centre of the channel. The scouring associated with high flow velocities in the centre of the channel and the 'water-falling' over the structure itself creates a deep, elongated pool.

Figure 6-20 Cross-vane structure with woody debris for habitat enhancement
(http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_contents.html)

• Deflectors are log and stone structures that constrict and divert water flow so that stream meanders and pools are formed by scouring and relocation of fine sediment. Wing deflectors should be placed so that water is diverted toward a stable section of the streambank. The main deflector log should be placed at a 35 degree angle from the streambank, and supported with a downstream brace log.

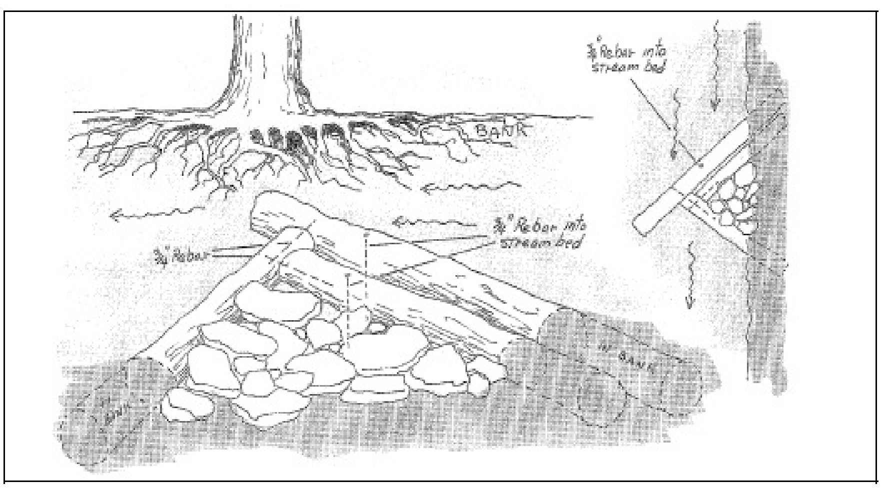


Figure 6-21 Deflectors
(http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_contents.html)

Benefits

- Stream bank rehabilitation and bio-stabilisation serves to decrease erosion, improve fisheries and wildlife, and increase the general health of the community.
- Fish and other aquatic organisms require snags, rocks and logs to shelter from predators and the sometimes strong currents as well as to reproduce.
- The in-stream structures reduce near-bank shear stress and stream power, while increasing centre channel shear stress and stream power to retain both flood-flow and sediment transport capacity. The velocity of water would be reduced so as to decrease erosion of the drain banks.
- The restoration process of stream banks may require the use of in-stream structures to create riffle/pool sequences, step/pool sequences, and improved aquatic habitat.
- Construction of hurdles, drops and weirs in lower reaches and drain modifications such as recreating meanders, providing riffles and laying back sides slopes in the upper reaches. The ability for the system to transport loads would be reduced.

Technical Considerations

In-stream structures should:

- Not cause upstream flooding or downstream erosion.
- Maintain the shear stress to move the largest size particle to maintain stability (competence);
- Decrease near-bank velocity, shear stress or stream power;
- Maintain channel capacity;
- Ensure stability of structure during major floods;
- Maintain fish passage at all flows;
- Provide safe passage or enhance recreational boating;
- Improve fish habitat;
- Be visually compatible with natural channels;
- Be less costly than traditional structures;
- Create maintenance-free diversion structures;

- Reduce bridge pier/footer scour, road fill erosion and prevent sediment deposition.
- In-stream structures may not be appropriate in channels with unstable banks.
- Felled trees in streams should be sufficiently anchored to avoid creating flow-impeding obstructions downstream.
- Maintain the stable width/depth ratio of the channel
- Boulders can be placed in most stream locations including riffles, runs, flats, glides, and open pools. Greatest benefits are likely to be achieved in currents > 0.61 m s^{-1}.

Cost Estimates

Total construction cost, including materials, machinery hire costs, consultant fees and labour, for a major riffle sequence (for example, four riffles of approximately 6 m stream span by 3 m in width) is estimated at \$16,000 - \$18,000 km^{-1}.

Water Corporation concrete drop structures are approximately 10 times more expensive to construct than riffles, typically costing in the order of \$35,000 each or \$120,000 km^{-1} (http://crcleme.org.au/Pubs/OPEN%20FILE%20REPORTS/OFR%20209/OFR%20209.pdf)

Monitoring and Maintenance

Confluences are prime areas for sedimentation build-ups leading to erosion they are also a point where monitoring is appropriate to identify portions of a catchment which contribute high levels of sediment, nutrient and flow. There may also be opportunities at the farm scale to adopt nutrient and sediment control structures.

6. 3 **Recommendation Measures**

Achieving behaviour change amongst agricultural landholders will require additional effort, particularly where the nutrients are derived from diffuse sources (e.g. fertiliser on grazing lands).

The following actions have been recommended to achieve cost-effective outcomes from investments in nutrient management in the Peel-Harvey catchments (URS, 2005):

- Adopt an investment strategy that focuses on gaining adoption of those BMPs that have been shown to deliver nutrient export reduction at least cost. Do not focus on BMPs that are suggested to deliver maximum benefits to the landholder.

- Recognise that a high level of direct government support will be required to match the public to private benefit mix. This will still achieve environmental outcomes at a lower cost than government support of inefficient BMPs that deliver a greater share of private benefits.

- Adopt an investment strategy to fund up-front capital costs and any gap between private benefits and operating and maintenance costs for the first five years.

- Aim to gain efficiencies in this approach of direct investment with the use of a Natural Resource Management (NRM) 'auction system' to target nutrient reduction investments. Use this system to ensure environmental benefits are delivered at least cost, and to target investments to BMPs and sub-catchments where nutrient reductions can be achieved at least cost.

- Use a 'NRM auction' approach to obtain contracts with landholders for the provision of target benefits and the maintenance and operation of BMP investments for ten years.

- Invest in biodiversity outcomes.

- Develop a product stewardship scheme with manufactures and importers of fertiliser to ensure those enterprises hold responsibility for appropriate use of their product – prevent the future sale of anything other than slow release products in susceptible areas. These enterprises should be responsible for outcomes when their product becomes a pollutant, especially when used in accordance with their recommendations.

- Support the direct investment via a 'NRM auction system' and the product stewardship scheme with ongoing education, skills, and group development. These mechanisms are still required to raise awareness of issues and gain acceptance of mechanisms to be used.

- Maintain the use of regulation as a 'safety net' for environmental management control. Do not target landuse change approaches.

- Investigate opportunities to use tradable permits between urban and agricultural sources, use this effort as a means to involve urban and rural communities in addressing the issue together.

- Undertake further research and development to ensure desired Redcoat and Alkaloam™ are available for use.

- Target extension programs to deliver information on BMPs and their benefits to farmers is required to achieve sub-catchment water quality targets.

It has been noted during the course of this study that there are a number of research projects on BMPs and case studies across Australia but the information is not readily accessible. There are different authorities, government agencies, research institutes and others in WA and the eastern states, dealing with similar issues, however, this information is dispersed and not easily accessible.

In the US there is a national database project “The International Stormwater Best Management Practices (BMP) Database Project” (ASCE/USEPA, 2006) where information is shared across different States and is readily accessible to the public. The database has over 300 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications. The overall purpose of the project is to provide scientifically sound information to improve the design, selection and performance of BMPs.

A similar knowledge base should be set up in Australia, where information is readily accessible and can be used by professionals to access and input information as needed.

Some of the gap information requiring further investigation identified from the literature includes:

- Effectiveness of various BMPs
- Cost of BMPs
- Design Guidelines
- Monitoring Guidelines
- Technical guidelines
- Impact of land use changes on catchment.

Findings from this study and from the Department of Agriculture (2006), highlight that the research and demonstration sites have concentrated mainly on limited BMPs such as perennial vegetation, effluent management, riparian vegetation, vegetated buffer swales, Alkaloam and fertiliser management. There are other BMPs that need to be fully investigated, in particular, in-stream techniques that improves water quality between the farm and the catchment.

6. 4 **Conclusions**

Information and data collected in the course of this study indicate that there are different authorities, government agencies and research institutes in WA and the eastern states, dealing with nutrient export from rural catchments in the rural drainage areas. Most of the research is focused on few BMPs relating to low stream orders. The relevant information regarding these BMPs and their impact on the catchment is dispersed and not easily accessible. There are no approved standards or guidelines on how the information is collected or measured, so it is difficult to compare one set of data with another with great confidence.

Uptake of BMPs by farmers is very low and represents a challenge to Catchment Managers. Indications from current research in Peel Harvey however, indicate that even with high BMP uptake by farmers, there is a limit to nutrient reduction efficiencies from farms, and there is a need to use other techniques, such as in-stream BMPs to reduce nutrient export to the catchment. There is currently very limited local research that demonstrates the suitability and effectiveness of these BMPs.

Government agencies should continue to inform farmers and growers about BMP options and water quality regulations through media and press that will help to achieve increased BMP implementation in the coastal areas. Government agencies can provide incentives and cost-sharing programs to farmers and growers to implement expensive BMPs.

SUGGESTIONS FOR FUTURE RESEARCH

Based on the findings of this study, following research tasks are identified as being worth further research. These are:

• This study to detect drought, waterlogging and micronutrient stress on pastures was planned for use of hand-held spectroradiometer of spectral reflectance range of 400-2500 nm that was not available and PIMA and NIRS were used instead. Future studies should use hand-held spectroradiometer of spectral reflectance range of 400-2500 nm. Field experiments should be conducted to grow annual ryegrass in waterlogged and saline areas especially in fine textured soils and aerenchyma properties of annual ryegrass should be studied in detail.

• The remote sensing and GIS techniques developed during the Ph.D. study should be used by different government agencies for temporal monitoring of waterlogging, salinity land degradation in other parts of the Wheatbelt of Western Australia.

• This study did not address the issue of downstream and off-site ecological and hydrological impacts of deep drainage water discharge into natural streams and rivers in the Wheatbelt of WA. A future study can address this problem.

• The winter season rainfall shows a downward trend and summer season rainfall in all of cities in the south-west of Western Australia. Futher studies are required to introduce summer crops like maize, sorghum and millets in the farming system of the Wheatbelt of Western Australia. The annual rainfall and summer season rainfalls have been increasing in the north of Western Australia. This increasing trend in annual rainfall and summer season rainfalls in the north of Western Australia should be studied in detail in future studies and risk of flooding in northern coastal towns should be studied further.

REFERENCES

Adams, M. L., Philpot, W. D. and Norvell, W. A. (1999) Yellowness Index: An Application of Spectral Second Derivatives to Estimate Chlorosis of Leaves in Stressed Vegetation, *International Journal of Remote Sensing*, Vol. 20, No. 18.

Adeney, J. A. (2001) Cyanobacterial issues in the Lake Powell/Torbay Inlet Drainage System, prepared by CSIRO Land and Water, Perth for Water and Rivers Commission Western Australia.

Adams, M. L., Wendell, A. N., William, D. P. and John, H. P. (2000) Spectral Detection of Micronutrient Deficiency in `Bragg' Soybean, *Agronomy Journal*, Vol. 92, pp. 261-268.

Agency Drainage Steering Committee, commissioned by the Water and Rivers Commission.

Agricultural nutrient management practices in the Peel-Harvey catchment (2004) Presented at the 7th International River Symposium, Brisbane Australia, Aug. 31st – 3rd Sept.

Agriculture Western Australia (1999) Managing Land Degradation Using Landuse Planning Processes. M iscellaneous Publication 62/99. Prepared by Land Assessment Pty Ltd. November 1999.

Aldakheel, Y. Y. and Danson, F. M. (1997) Spectral Reflectance of Dehydrating Leaves: Measurements and Modelling., *International Journal of Remote Sensing*, No. 18, pp. 3683-3690.

Ali, R. and Coles, N. (2001) Drainage options and their use in Wheatbelt landscapes in Western Australia. In Proceedings of the Wheatbelt Valleys Conference. Water and Rivers Commission, Perth.

Ali, R., Hatton, T., George, R., Byrne, J. and Hodgson, G. (2004a). Evaluation of the impacts of deep open drains on groundwater levels in the Wheatbelt of Western Australia. Australian Journal of Agricultural Research, vol 55, pp 1159-1171.

Ali, R., Hatton, T., George, R., Lambert, T., Byrne, J. and Hodgson, G. (2004b). Evaluation of the impacts of deep open drains on soil root zone salinity at Narembeen in the wheatbelt of Western Australia. In proceedings Ist National Salinity Engineering Conference "Engineering Salinity Solutions"; 9-12 November, Perth, Western Australia, pp 89-94.

Ali, R., Hatton, T., Lambert, T., Byrne, J., Hodgson, G. and George, R. (2004c). An assessment of the quality and quantity of discharge from deep open drains in Narembeen; wheatbelt of Western Australia. In proceedings Ist National Salinity Engineering Conference "Engineering Salinity Solutions"; 9-12 November, Perth, Western Australia, pp 84-88.

Allison, G.B. and Hughes, M.W. (1983) The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. *J. of Hydrol*ogy Vol. 60. pp.157-73.

Allen, W. A. and Richardson, A. J. (1968) Interaction of Light with a Plant Canopy, Journal of the Optical Society of America, Vol. 58, pp. 1023-1028.

ARMCANZ & ANZECC (2000) National Water Quality Management Strategy - Australian Urban Stormwater Management Guidelines, Australian and New Zealand Environment and Conservation Council, Canberra, Australian Capital Territory.

ASCE/USEPA. (2006) International Stormwater Best Management Practices (BMP) Database, (http://www.bmpdatabase.org).

Australian Agriculture Assessment (2001) National Land and Water Resources Audit (http://www.apl.au.com/media/5826%20Resource%20Manual%20%2D%2022%20July%202003%2Epdf).

Bettenay, E. (1978) Deep drainage as a method of treating saltland. *Journal of Agriculture Western*. Australia 19:110-111.

Bowman, W. D. (1989) The Relationship between Leaf Water Status, Gas Exchange, and Spectral Reflectance in Cotton Leaves, *Remote Sensing of Environment*, Vol. 30, No. 3, pp. 249-255.

Bradby K (1997) Peel–Harvey: The decline and rescue of an ecosystem, Greening the Catchment Taskforce, Mandurah, Western Australia.

Bureau of Meteorology (2007) Tropical Cyclone Information for Australia and Southern Hemisphere sourced from the Bureau of Meteorology website (http://www.bmpdatabase.org).

Caccetta P.A. (1997) Remote Sensing, Geographical Information Systems (GIS) and Knowledge-Based Methods for Monitoring Land Condition, Ph.D. Thesis, School of Computing, Curtin University of Technology.

Caccetta, P.A. (1999), Technical note – A simple approach for reducing discontinuities in digital elevation modes (dems), Internal task report, CSIRO Mathematical and Information Sciences, Floreat, Perth, Western Australia.

Carter, G. A., (1991) Primary and secondary eVects of water content on the spectral reflectance of leaves. *American Journal of Botany*, 78, 916- 924.

Chaudhary, T. N., V. K. Bhatnagar and S. S. Prihar (1974) Growth Response of Crops to Depth and Salinity of Ground Water, and Soil Submergence. I. Wheat (Triticum aestivum L.), *Agron J.*1974; 66: 32-35

Chesapeake Bay Program (2006) Best Management Practices for Sediment Control and Water Clarity Enhancement (http://www.chesapeakebay.net/pubs/waterqualitycriteria/doc - Ag_BMP_Defns.pdf)

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988) Applied Hydrology. McGraw Hill, New York.

Cibula, W. G., Zetka, E. F., and Rickman, D. L. (1992) Response of Thematic Mapper bands to plant water stress. *International Journal of Remote Sensing*, 13, 1869-1880.

Coles, N.A., George, R.J. and Bathgate, A.D. (1999) An assessment of the efficacy of deep drains constructed in the wheatbelt of Western Australia. Department of Agriculture Bulletin 4391.

Commission Greenop, B. and Robb, M. (2002) Improving water quality in the Kent Street Weir, Canning River Western Australia, through artificial oxygenation. Swan River Trust, Western Australia.

Cox N (2002) Beynon Road drainage demonstration design and works program, Dumbleyung Water Management Strategy, Bunbury, Australia.

Cronin D (1998) (unpublished Honours thesis) The effectiveness of 'Streamlining'in improving the water quality of agricultural drains in the Peel-Harvey Catchment, Murdoch University, Perth, Western Australia.

CSIRO (2001) Climate change projections for Australia, CSIRO, Aspendale.

CSIRO (2005) Farming Ahead, No. 159 April, 2005 (http://www.csiro.au/files/files/p350.pdf)

Cochrane, M. A. (2000) Using Vegetation Reflectance Variability for Species Level Classification of Hyperspectral Data, *International Journal of Remote Sensing*, Vol. 21, No. 10, pp. 2075-2087.

Curran, P. J. (1985) Aerial Photography for the Assessment of Crop Condition: A Review, Applied Geography, Vol. 5, No. 4, pp. 347-360.

Curran, P. J. (1989) Remote sending of foliar chemistry. *Remote Sensing of Environment*, 30, 271–278.

Danson, F. M., Steven, M. D., Malthus, T. J., and Clark, J. A. (1992) High spectral resolution data for determining leaf water content. *International Journal of Remote Sensing*, 13, 461- 470.

Department of Agriculture & Food, (2006) Targeted assistance to intensive agricultural activities in the Peel-Harvey Coastal Plain Catchment.

D'Angelo, A., Eskandari, A. and Szidarovszky, F. (1998) Social Choice Procedures in Water-Resource Management, Journal of Environmental Management, 52, 203-210.

Davis, R. and Koop, K. (2006) Eutrophication in Australian rivers, reservoirs and estuaries – a southern hemisphere perspective on the science and its implications. Hydrobiologia 559, 23-76.

Deeley, D. (2002) Water Resources Management Strategy for the Busselton-Dunsborough Region – Water Resources Management Issues. Prepared by Acacia Springs Environmental for the Water and Rivers Commission.

Del Marco, A (2007) Drainage reform plan Peel-Harvey coastal catchment volume one: policy and governance discussion paper, A report by Ironbark Environmental for the Peel Harvey Catchment Council, Mandurah, Western Australia.

Department of Agriculture & Food, (2006) Targeted assistance to intensive agricultural activities in the Peel-Harvey Coastal Plain Catchment.

Department of Agriculture & Food, Bulletin 4513: Scott Coastal Plain: a strategy for a sustainable future.

Department of Agriculture, (2003) West Australia, Farmnote No. 76/2003.

Department of Environment, September, (2004) Aggregated Emissions of Total Nitrogen And Total Phosphorus To The Vasse-Wonnerup Catchment, Western Australia.

Department of Primary Industries, (2008) Organic Farming: Perennial Pasture Management, Agriculture Note, AG1278, Victoria.

Department of Water, (2007) Stormwater Management Manual for Western Australia.

Dillaha, T.A., (1989) Water Quality Impacts of Vegetative Filter Strips, ASAE. Paper No. 89-2043

Dogramaci, S. and Degens, B. (2003) Review of Engineering and Safe Disposal options. Waters and Rivers Commission, pp. 24, East Perth.

Duxbury, (2005) Information Is Not Enough! Integrating Research And Value Judgements To Change Catchment Management Is Central To Success, Watershed Torbay Western Australia, WA.

Duxbury, (2005) Watershed Torbay Western Australia - Beyond awareness to behaviour change.

DPI, WA, (2005) The grazing of Sheep In the Pastoral Areas Of Western Australia Best Management Practice – July.

Ecotones & Associate (2002) An Introduction to ArcView 3.2a, Department of Agriculture and Food, Katanning.

Elvidge, C. D. (1990) Visible and near infrared red reflectance characteristics of dry plant materials. *International Journal of Remote Sensing*, 11, 1775–1795.

English, L.B. (1994) Country Drainage - Busselton Drainage District, Water Authority of Western Australia, ISBN 0 7309 5264 9, Leederville, Western Australia.

English L (1995) Future Management and Funding of Country Drainage, Water Authority, Perth.

English L & Doubikin R (1994) Country Drainage – Waroona, Harvey & Roelands Drainage Districts, Water Authority, Perth.

Ecotones & Associates, (2002) Best Management Practices for Nutrient Reduction in Wilson Inlet and Torbay Catchments, Natural Heritage Trust.

Environmental Protection Authority (2007) Draft Water Quality Improvement Plan for the Rivers and Estuary of the Peel-Harvey System, Environmental Protection Authority, Perth, Western Australia.

Erol, C. (1999) South West Irrigation area farm survey (Corresponding author: cerol@agric.wa.gov.au) South West Irrigation, WA.

Fahrner, S. (2002) Groundwater Nitrate Removal Using a Bioremediation Trench, Honours Thesis, University of Western Australia, Department of Environmental Engineering.

Fangmeier, D.D., Wlliam, J.E., Workman, S.T., Huffman, R.L., Schwab, G.O (2006) Soil and Water Conservation Engineering, 5th Edition, Thomson Delmar Learning, N.Y., USA.

Ferdowsian, R., George, R., Lewis, F., McFarlane, D., Short, R. & Speed, R. (1996) The extent of dryland salinity in Western Australia. Proceedings of the 4th National Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands, Albany, WA, March 1996, pp. 89-97.

Fletcher, T.D., Duncan, H.P., Poelsma, P. and Lloyd, S.D. (2003) Stormwater Flow, Quality and Treatment: literature review, gap analysis and recommendations report, NSW Environmental Protection Authority and Institute for Sustainable Water Resources, Department of Civil Engineering, Monash University, Melbourne, Victoria.

Flavell, D. J. and Belstead, B. S. (1986) Losses for design flood estimation in Western Australia. Hydrol. Water Resour. Symp., I. E. Aust., 86(13), 203 - 208.

Ford, P. W. and Bormans, M. (2000) Nitrogen transformations in freshwater sediments. In 'Nitrogen Workshop 2000: Sources, transformations, effects and management on nitrogen in freshwater ecosystems.' Melbourne. (Eds Hart, B. T. and Grace, M. R.) pp. 91-95. (Land and Water Australia).

Gao, B. C. (1996) Ndwi- a Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space., *Remote Sensing of Environment*, No. 58, pp. 257-266.

Gardner, A. (1999) Review of Law and Legislation on Rural Drainage. For the Inter-Agency Drainage Steering Committee, commissioned by the Water and Rivers Commission
.

Gerritse, R.G. (1990) Impact of Horticultural Landuse On Water Quality in the Darling Range and Coastal Plain of W.A.. In: Proceedings of a seminar "Horticulture and the Environment", Mandurah, 7-8 June 1990. Western Australian Dept.of Agriculture, No. 20/90, Agdex 200/00.

George, R.J. (1991) Management of sandplain seeps in the wheatbelt of Western Australia, Agricultural and Water Management, No. 18, pp 85-104.

George, P.R. and Nulsen, R.A. (1985) Saltland drainage: case studies. Journal of Department of Agriculture 26:115-118.

GHD Pty Ltd (2005) Draft Report. Groundwater Treatment Curtain Trial - Preliminary Design, GHD Pty Ltd, Perth.

Gilliom, Robert J. (1984) Tools for assessing lake eutrophication in the Puget Sound Region, Washington. Third annual conference proceedings on Lake and Reservoir Management; 1983 October 18-20; Knoxville, Tennessee. U.S. Environmental Protection Agency: Washington, D.C. 32-39.

Hajkowicz, S.A., McDonald, G.T. and Smith, P.N. (2000b) An Evaluation of Multiple Objective Decision Support Weighting Techniques in Natural Resource Management, *Journal of Environmental Planning and Management*, 43, 4, pp. 505-518.

Hart, B. T. and Grace, M. R. (2000) Workshop report. In 'Nitrogen Workshop 2000: Sources, transformations, effects and management on nitrogen in freshwater ecosystems'. Occasional report 10/00. Melbourne. (Eds Hart, B. T. and Grace, M. R.) pp. 5-29. (Land and Water Australia, Canberra)

Hatton, T. J., (2002) Engineering our way forward through Australia's salinity challenge, Technical Report 4/02 CSIRO Land and Water, Perth.

Heddinghause, T. R. and Sabol, P. (1991) A Review of the Palmer Drought Severity Index and Where Do We Go from Here, Proc. of the Seventh Conference on Applied Climatology, pp. 242-246.

Hill, A.R. (1996) Nitrate removal in stream riparian zones. *J. Environ. Qual.* 25:743-755.

Hunt, E. R. Jr., (1991) Airborne remote sensing of canopy water thickness scaled from leaf spectrometer data. *International Journal of Remote Sensing*, 12, 643-649.

Hunt, E. R. Jr., and Rock, B. N. (1989) Detection of the change in leaf water content using near- and middle-infrared reflectance. *Remote Sensing of Environment*, 30, 43- 54.

Hunter, H. M. (2000) Agricultural sources of nitrogen to acquatic systems. In 'Nitrogen Workshop 2000: Sources, transformations, effects and management on nitrogen in freshwater ecosystems.' Melbourne. (Eds Hart, B. T. and Grace, M. R.) pp. 74-79 (Land and Water Australia).

Indian Ocean Climate Initiative (2004) How Has Our Rainfall Changed? The South West (http://www.geocatch.asn.au/pages/framesaction.html).

IPCC (2007) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC (Intergovernmental Panel on Climate Change) (2007b) Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, England.

Jackson, R. and Ezra, C. E. (1985) Spectral Response of Cotton to Suddenly Induced Water Stress, *International Journal of Remote Sensing*, Vol. 6, No. 1, pp. 177-185.

Jackson, R. D. (1982) Canopy Temperature and Crop Water Stress, In Advances in Irrigation, edited by D. Hillel (New York: Academic Press), pp. 43-85.

Jackson, S. H. (1991) Relationships between Normalized Leaf Water Potential and Crop Water Stress Index Values for Acala Cotton, Agricultural Water Management, Vol. 20, No. 2, pp. 109-118.

KABAY rehabilitation, environmental and biological Consultants Pty Ltd, (2002) Native Plant Species to be Used in Stabilization and Enhancement of Water Corporation Rural Main Drains in the South West Drainage Districts.

Keipert, N., Weaver, D., Summers, R. and S. Neville (2007) Guiding BMP adoption to improve Water Quality in various Estuarine Ecosystems in Western Australia. 11th International Conference on Diffuse Pollution (26-31 August 2007, Belo Horizonte, Brazil)

Kelsey, P. (2004) Nutrient Export in Surface and Groundwater Under Various Land Uses, in Land Development in Areas of High Water Table Forum Proceedings, Institution of Engineers, Aust. in association with Urban Development Institute of Australia.

Knight R. (1990) The Role of Perennial Plants in Reducing the Movement of Phosphorus From Pastures to Waterways in Western Australia. Western Australian Department of Agriculture.

Lavell K., Summers R.N., Weaver D.M., Clarke M.F., Grant J. and Neville S.D. (2004) An Audit Of The Uptake Of Agricultural Nutrient Management Practices in The Peel-Harvey Catchment.

Lee, S.Y. and Gilkes, R.J. (2005). Ground-water geochemistry and composition of hardpans in southwestern Australian regolith. Geoderma, 126, 59-84.

Leschenault Landscape Water Management Plan (2006) Drainage Master Plan, Leschenault Catchment Council.

Lovett, S. and Price, P. (1999) Riparian land management technical guidelines, Volumes
1 & 2. Lands and Water Resources Research and Development Corporation, Canberra.

Lloyd, S.D., Wong, T.H.F, and Chesterfield, C.J. (2002) Water Sensitive Urban Design A Stormwater Management Perspective. Industry Report No. 02/10. Cooperative Research Centre for Freshwater Ecology, Melbourne, Victoria. Referenced heavily in Fletcher et al. (2003).

Luke, G.J., Burke, K.L. and O'Brien, T.M. (2003) Evaporation Data for Western Australia. Resource Management Technical Report No. 65, Department of Agriculture Western Australia.

Madramootoo, C.A., Kaluli, W.J., Zhou, X., MacKenzie, A.F. and Smith, D.L. (1995) Water table management and cropping systems for environmental sustainability. ASAE Paper No. 95-2360, St. Joseph, MI: ASAE.

Madramootoo, C.A., Papadopoulos, A. and Dodds, G.T. (1993) Agronomic and environmental benefits of water table management. J. Irr. and Drain. Engineering, ASCE, 119(6): 1052-1065.

Mann, A.W. (1983). Hydrogeochemistry and weathering on the Yilgarn Block, Western Australia – ferrolysis and heavy metals in continental brines. Geochim. Cosmochim. Acta, 47, 181-190.

Martin, M. E. and Aber, J. D. (1997) High Spectral Resolution Remote Sensing of Forest Canopy Lignin, Nitrogen, and Ecosystem Processes, Ecological Applications, Vol. 7, No. 2, pp. 431-443.

Matson, P., Johnson, L., Billow, C., Miller, J. and ., R. P. (1994) Seasonal Patterns and Remote Spectral Estimation of Canopy Chemistry across the Oregon Transect., Ecol. Appl.,, Vol. 4, pp. 280-298.

McAlpine, K. W., Spice, J. F. & Humphries, R. (1989) The environmental condition of the Vasse-Wonnerup wetland system and a discussion of management options. Environmental Protection Authority Technical Series No 31.

McFarlane, D. (2005) Context Report on South West Water Resources For: Expert Panel Examining Kimberley Water Supply Options Client Report to WA Government, CSIRO.

McFarlane, D.J. and Williamson, D.R. (2002) An overview of water logging and salinity in southwestern Australia as related to the 'Ucarro' experimental catchment, Agricultural Water Management, Vol. 53, No. 1-3, pp. 5-29.

McFarlane, D.J., Wheaton, G.A., Negus, T.R. and Wallace, J.F. (1992) Effects of waterlogging on crop growth and pasture production in the Upper great Southern, Western Australia. Tech. Bulletin No. 86, Agriculture Western Australia.

McKergow L.M., Weaver D.M., Prosser I.P., Grayson R.B. and Reed A.E.G. (2002) Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *Journal of Hydrology*; 270, 253-272

McVicar, T. R. and Jupp, D. L. B. (1998) The Current and Potential Operational Uses of Remote Sensing to Aid Decisions on Drought Exceptional Circumstances in Australia: A Review, Agricultural Systems, Vol. 57, No. 3, pp. 399-468.

Meinck G. (2003) Drainage System: A Service Providers Perspective, Water Corporation, Western Australia (presented at the Drainage Management Forum Swan–Canning Catchment).

Mickelson, S. K., J. L. Baker, and S. I. Ahmed. (2003) Vegetative filter strips for reducing atrazine and sediment runoff transport. J. Soil Water Conserv 58:359–367.

Moore I.D., Gallant J.C. and Guerra, L. (1993) Modelling the spatial variability of hydrological processes using GIS in: HydroGIS 93: Application of Geographical Information Systems in Hydrology and Water Resources Management. Proceedings of Vienna Conference, April 1993. IAHS Publ. No. 211. P 161-169.

Monaghan, R.M., de Klein, C.A.M., Wilcock, R.J., Smith, L.C., & Thorrold, B.S. (2005) Managing nutrient losses and greenhouse gas emissions from dairy farms within the Bog Burn catchment, Southland. In Developments in fertiliser application technologies and nutrient management. (Eds L.D. Currie and J.A.

Hanly). Occasional Report No. 18. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. pp151-161.

Mundy, G. N., Nexhip, K. J., Austin, N. R. and Collins, M. D. (2003) The influence of cutting and grazing on phosphorus and nitrogen in irrigation runoff from perennial pasture. Australian Journal of Soil Research 41, 675-685.

Neville S.D., Weaver D.M., Summers R.N., Lavell K. (2005) Farm gate nutrient balances in south west Western Australia – an eco-efficiency indicator? Environment Institute of Australia and New Zealand, Environmental.

Newham L, Rutherford J. C, Croke B. F. W., October, 2005. A conceptual model of particulate trapping in riparian buffers. CSIRO Land and Water Technical Report 21/05.

Otto, C. and Salama, R.B. (1994) Linked enhanced discharge - Evaporative disposal systems. In Groundwater - Drought, Pollution and Management (Reeve, R and Watts, J., eds), A.A. Balkema, Rotterdam, pp. 35-44.

Parkyn, S. (2004) Review of riparian buffer zone effectiveness. MAF technical paper No. 2004/05 ISBN No: 0-478-07823-4 ISSN No: 1171-4662.

Peel Development Commission (2006) Peel-Harvey Coastal Catchment Water Sensitive Urban Design Technical Guidelines, Peel Development Commission, Mandurah.

Peel-Harvey Catchment Council (2007) Drainage Reform Plan, Peel-Harvey Coastal Catchment Volume Two: Best Management Practices.

Pen, L. et al. (1999) Review of Inland Drainage. Unpublished draft by the Waters and Rivers Commission Drainage Group.

Penuelas, J., Filella, I., Biel, C., L.Serrano and R.Save (1993) The Reflectance at the 950-970 Nm Region as an Indicator of Plant Water Status, International Journal of Remote Sensing, Vol. 14, No. 10, pp. 1887-1905.

Penuelas, J., Filella, I. and Sweeano, L. (1996) Cell Wall Elastivity and Water Index (R970nm/R900nm) in Wheat under Different Nitrogen Availabilities, International Journal of Remote Sensing, Vol. 17, pp. 373-382.

Penuelas, J., Gamon, J. A., Fredeen, A. L., Merino, J. and Field, C. B. (1994) Reflectance Indices Associated with Physiological Changes in Nitrogen- and Water-Limited Sunflower Leaves, Remote Sensing of Environment, Vol. 48, No. 2, pp. 135-146.

Penuelas, J., Pinol, J., Ogaya, R. and Filella, I. (1997) Estimation of Plant Water Concentration by the Reflectance Water Index WI (R900/R970), International Journal of Remote Sensing, Vol. 18, No. 13, pp. 2869 - 2875.

Penuelas, J., Save, R., Marfa, O. and Serrano, L. (1992) Remotely Measured Canopy Temperature of Greenhouse Strawberries as Indicator of Water Status and Yield under Mild and Very Mild Water Stress Conditions, Agricultural and Forest Meteorology, Vol. 58, No. 1-2, pp. 63-77.

Pilgrim, D.H. (ed.) (2001) Australian Rainfall and Runoff (AR&R), A guide to flood estimation. Vol. 1. The Institution of Engineers Australia: Barton, ACT.

Powell J. M., (1998) Watering the Western Third: Water, Land and Community in Western Australia 1826-1998, Water and Rivers Commission, Government of Western Australia.

Rasiah, V., Armour, J. D., Yamamoto, T., Mahendrarajah, S. and Heiner, D. H. (2003) Nitrate dynamics in shallow groundwater and the potential for transport to off-site water bodies. Water Air and Soil Pollution, 147: 183–202.

Rassam, D., Fellows, C., DeHayr, R., Hunter, H., Bloesch, P. and Beard, N. (2003) Interaction of surface water and groundwater and its potential effects on denitrification in riparian buffers. In 'The Institution of Engineers, Australia. 28th International Hydrology and Water Resources Symposium'. Wollongong, Australia. (Ed. Boyd, M. J.) pp. 219-224. (The Institution of Engineers, Australia.)

Regeneration Technology Pty Ltd (1999) Best Management Practices For Rural Drains In The South West And South Coast Drainage Districts Of Western Australia, Draft Practitioners Reference Manual.

Ridley A.M., White R.E., Helyar K.R., Morrison G.R., Heng L.K. & Fisher R. (2001) Nitrate leaching loss under annual and perennial pastures with and without lime on a duplex (texture contrast) soil in humid south-eastern Australia, *European Journal of Soil Science* vol. 52, pp. 237-52.

Ridley A.M., Christy B.P., White R.E., McLean T. and Green R. (2003). North-east Victoria SGS National Experiment site: water and nutrient losses from grazing systems on contrasting soil types and levels of inputs. Australian Journal of Experimental Agriculture 43, 799-815.

Saha, S.K., M. Kudrat, and S.K. Bhan, (1990) Digital processing of Landsat TM data for wasteland mapping in parts of Aligarh District, Uttar Pradesh, India. International Journal of Remote Sensing, vol.11: 485-492.

Salama, R., Hatton, T.J., Elder, G.M. and Ye, L. (1997) Hydrogeological characterisation of catchments using Hydrogeomorphic Analysis of Regional Spatial Data (HARSD): Characterisation of Axe Creek Catchment, Victoria, Australia. In Subsurface Hydrological response to Land Cover and Land Use Change (Ed. M. Tanaguchi), Kluwer Academic Publishers.

Salama, R.B., Otto, C.J., Bartle, G.A. and Watson G.D. (1994) Management of saline groundwater discharge by long term pumping in the wheatbelt of Western Australia. J. Applied Hydrogeology, 2: 19-33.

Schmidt, K. S. and Skidmore, A. K. (2001) Exploring Spectral Discrimination of Grass Species in African Rangelands, International Journal of Remote Sensing, Vol. 22, No. 17, pp. 3421-3434.

Serrano, L., Filella, I. and Penuelas, J. (2000) Remote Sensing of Biomass and Yield of Winter Wheat under Different Nitrogen Supplies, Crop Sci, Vol. 40, No. 3, pp. 723-731.

Schipper, L.A., and M. Vojvodic-Vukovic. (2001) Five years of nitrate removal, denitrification and carbon dynamics in a denitrification wall. Water Res. 35:3473–3477.

Shibayama, M., Takahashi, W., Morinaga, S. and Akiyama, T. (1993) Canopy Water Deficit Detection in Paddy Rice Using a High Resolution Field Spectroradiometer, Remote Sensing of Environment, No. 45, pp. 117-126.

Siddiqi, M.J., Corner, R. and Henry, D. (2004) Can Remote Sensing be used to identify drought and waterlogging stresses in pastures? The 12th Australasian Remote Sensing and Photogrammetry Conference, Fremantle, Western Australia 18-22 October 2004.

Siddiqi, M.J. (2002) The influence of deep drainage on the crop growth on duplex soil in Dumbleyung, Agriculture Western Australia, South Perth.

Siddiqi, M.J. (2002) Drain effect on crop production: crop sampling trials. Report for the Dumbleyung Water Management Strategy, Department of Agriculture Katanning.

Siddiqi, M.J. and Brockman, H. (2002) Blackwood Catchment: Beaufort Zone, Catchment Appraisal 2002, Resource Management Technical Report 243, Department of Agriculture.

Simpson, J.T., and Reckhow, K.H.. (1979) A method for the prediction of phosphorus loading and lake trophic quality from land-use projections. East Lansing, Mi.: Department of Resource Development, Michigan State University.

SKM (2003) Integrated Nearshore Marine Monitoring Program for Southern Geographe Bay. Report to the Water Corporation of Western Australia.

Speed, R.J. and Simons, J.A. (1992) Deep drains - a case study and discussion. Department of Department of Agriculture Division of Resource Management Technical Report 133.

Strahler, A.N. (1952) Hypsometric (area-altitude) analysis of erosional topography. Bulletin of the Geological Society of America, 63, 1117-1142.

Summers, R.N., Rivers, M.R. and Clarke, M.F, (2002) The Use Of Bauxite Residue To Control Diffuse Phosphorus Pollution In Western Australia, Proceedings of the 6th International Alumina Quality Workshop.

Summers, R.N., Rivers, M.R. and Clarke, M.F. (2002) Department of Agriculture, Western Australia. The Use Of Bauxite Residue To Control Diffuse Phosphorus Pollution In Western Australia — A Win–Win–Win Outcome. Proceedings of the 6th International Alumina Quality Workshop, 2002.

Tapley, I., Pirlo, M.C. and Gray, D., (2004). Spectral mineralogy, soil and water chemistry associated with the Narembeen drain network and Seagroatt Nature Reserve. CSIRO Exploration and Mining, Exporation and Mining Report 1235R for Dept. Conservation and Land Management, WA.

Taylor, A., (2003) An Introduction to Life-cycle Costing Involving Structural Stormwater Quality Management Measures. Technical Paper. Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria.

Taylor, A.C. (2005a) Structural Stormwater Quality BMP Cost/Size Relationship Information from the Literature (Version 3), Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria.

Taylor A., (2005b) Guidelines For Evaluating The Financial, Ecological And Social Aspects Of Urban Stormwater Management Measures To Improve Waterway Health Technical CRCCH Report Report 05/11.

Taylor, A.C. and Wong, T.H.F. (2002) Non-structural Stormwater Quality Best Management Practices – a literature review of their value and life cycle costs, Technical Report 02/13, Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria.

Taylor, G. and Dehaan, R. (2000) Salinity mapping with hyperspectral imagery, Remote Sensing, UNSW, NSW.

Taylor, S. L., Raun, W. R., Solie, J. B., Johnson, G. V., Stone, M. L. and Whitney, R. W. (1998) Use of Spectral Radiance for Correcting Nitrogen Deficiencies and Estimating Soil Test Variability in an Established Bermudagrass Pasture, J. Plant Nutr., Vol. 21, No. 11, pp. 2287-2302.

Tetlow, S. (2001) Drain effect on crop production: crop sampling trials. Report for the Dumbleyung Water Management Strategy, Department of Agriculture Katanning.

Tian, Q., Tong, Q., Pu, R., Guo, X. and Zhao, C. (2001) Spectroscopic Determination of Wheat Water Status Using 1650-1850 Nm Spectral Absorption Features, International Journal of Remote Sensing, Vol. 22, No. 12, pp. 2329-2338.

Tripathi, N.K., Rai, B.K., and Dwivedi, P. (1997) Spatial modeling of soil alkalinity in GIS environment using IRS data, 18th Asian conference on remote sensing, Kualalampur, pp.A.8.1-A.8.6.

Tomer, M. D., Anderson, J. L. and Lamb, J. A. (1997) Assessing Corn Yield and Nitrogen Uptake Variability with Digitized Aerial Infrared Photographs, Photogrammetric Engineering and Remote Sensing, Vol. 63, No. 3, pp. 299-306.

Turner, M. and Carter, D (1991) Down the Drain. The Story of Events and Personalities Associated with 125 Years of Drainage in the South-East of South Australia. South-Eastern Drainage Board, Adelaide.

U.S. Department of Agriculture (USDA), (1998) Riparian Forest Buffer, Conservation Practice Job Sheet, Natural Resources Conservation Service (NRCS).

URS (2003) Water Sensitive Urban Design Technical Guidelines for Western Sydney. Draft report prepared for the Upper Parramatta River Catchment Trust, Sydney, New South Wales.

URS (2005) Implementation Measures that Support, Influence, Encourage or Require Uptake of Best Management Practices for Nutrient Management.

URS (2006) Benefit-cost analysis (BCA) of arterial drainage options for the Dumbleyung Zone.

URS (2007) State of Play Peel-Harvey Eastern Estuary Catchment Environmental Assessment Discussion Paper.

URS (2007) Hydrogeology Investigation Buntine-Marchagee Natural Diversity Recovery Catchment, URS Unpublished Report to Department of Environment and Conservation dated 6 June, 2007, Report No. 42906201

URS (2007) Panorama Project Surface Water Hydrology, URS Unpublished Report to CBH Resources dated 10 August, 2007, Report No. 42906372

URS (2007) Runoff Attenuation Assessment of the Cleo/Sunrise Pit Sunrise Dam Gold Mine, URS Unpublished Report to Anglo Gold Ashanti Australia Ltd dated 18 July, 2007, Report No. 42906466/658-F8286.

URS (2008) Collect Information and Data on Rural Drainage to Develop a BMP Toolbox for six coastal districts of Western Australia, URS Unpublished Report to Department of Water, Bunbury, dated 26 May, 2008.

Wallbrink, P.J., Martin, C.E. and Wilson, C.J. (2003) Quantifying the contributions of sediment, sediment-P and fertiliser-P from forested, cultivated and pasture areas at the landuse and catchment scale using fallout radionuclides and geochemistry. Soil Tillage Res. 69:53–68.

Water and River Commission, (2000) Flooding in Western Australia, Water Facts.

Weaver D.M., Neville S. Summers, R. N., Deeley D.M. and Clarke M.F. (2004) reducing Nutrient Sischarge from Agriculture through the Implementation of BMPs – How Far Can we Go?. Department of Agriculture, Western Australia.

Webber, T. (2001) and Tony Weber (2002) Senior Waterways Program Officer (Water Quality), Brisbane City Council, Queensland, personal communication; not seen, cited in Taylor and Wong (2002).

Weber, T. (2001) & (2002) Tony Weber, Senior Waterways Program Officer (Water Quality), Brisbane City Council, Queensland, personal communication. Cited in Taylor and Wong (2002).

Western Australian Water Resources Council, (1986).

Wischmeier, W.H. and Smith, D.D. (1958) Rainfall Energy and its Relation to Soil Loss. Am. Geophysc. Union Trans. 39, 285-291.

WML Consultants (2005) Geocatch Drainage Master Plan – Interim Draft Report, A report prepared by Graham Holtfreter to Geocatch, Busselton.

Wong, T.H.F., Wootton, R.M. and Fabian D. (1996) A Solids Separator Using a Continuous Deflective System. Department of Civil Engineering, Monash University, Melbourne.

Yesertener, C. (2005) Impacts of climate, land and water use on declining groundwater levels in the Gnangara Groundwater Mound, Perth, Australia, Australian Journal of Water Resources, Vol 8, No 2, pp143-152.

Zagolski, F., Pinel, V., Romier, J., Alcayde, D., and Fontanari, J. (1996) Forest canopy chemistry with high spectral resolution remote sensing. International Journal of Remote Sensing, 17, 1107–1128

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

APPENDIX 1-1 COMPOSITION OF THE NUTRIENT SOLUTION USED IN THE NUTRIENT STRESS STUDY TITLE

Nutrient	Concentration of stock solution ($g\ L^{-1}$)	Final Concentration ($mg\ L^{-1}$)	Molarity
Macronutrients [a]			
$CaCl_2.2H_2O$	294	294	2.0 mM
K_2SO_4	65	261	1.5 mM
$MgSO_4.7H_2O$	246	246	1.0 mM
KNO_3	101	101	1.0 mM
KH_2PO_4	33.8	33.8	0.25 mM
FeNaEDTA	26.3	26.3	0.072 mM
Micronutrients [b]			
H_3BO_3	3.09	3.09	0.05 mM
$MnSO_4.4H_2O$	2.23	2.23	0.01 mM
$ZnSO_4.7\ H_2O$	0.288	0.288	1.0 µM
$CuSO_4.5\ H_2O$	0.25	0.25	1.0 µM
$(NH_4)_6Mo_7O_{24}.4\ H_2O$	0.088	0.088	0.07 µM
$CoCl_2.6\ H_2O$	0.048	0.048	0.2 µM

a 50 mL of each stock solution was used to prepare 50 L of nutrient solution with the exception of K_2SO_4 in which 4 mL of stock solution was used due to its relative insolubility

b 5 mL of each stock solution was used to prepare 50 L of nutrition solution

APPENDIX 1-2. SOIL ANALYSIS OF WONGAN LOAM AND WASHED WHITE SAND

	Washed White Sand	Wongan Loam Soil Average
N (mg kg^{-1})	2	11.25
P (mg kg^{-1})	2	49.25
K (mg kg^{-1})	13	416.75
S (mg kg^{-1})	4.3	4.85
Reactive Fe (%)	246	842.25
DTPA Mn (mg kg^{-1})	0.76	6.245
Zn (mg kg^{-1})	0.06	0.7625
Cu (mg kg^{-1})	0.06	4.4225
DTPA Fe (mg kg^{-1})	2.46	6.2375
Org. C %	0.1	1.0175
Conductivity DS/m	0.013	0.13775
pH ($CaCl_2$)	6.2	7.3
pH (H_2O)	6.7	8.05
Exc. Ca meq/100g		16.5825
Exc. Mn meq/100g		5.49
Exc. Na meq/100g		0.485
Exc. K meq/100g		1.0625

APPENDIX 1-3: ANALYSIS OF THRIVE SOLUTION APPLIED TO PLANTS FOR GERMINATION

Thrive Analysis	(%)
N	27
P	5.5
K	9
S	0.22
Fe	0.18
Mg	0.5
Mn	0.04
Zn	0.02
Br	0.005
Cu	0.005
Mo	0.002

APPENDIX 1-4: ONE-WAY ANOVA TEST FOR DROUGHT WATERLOGGING STRESS STUDY

21/02/2004	Control	Waterlogged	Drought
RWC (%)	70.7	64.4	60.5

Wavelength 1666 nm Alpha= 0.05

Groups	*Variance*	*P-value*	*Count*
Control	2.318188	0.006574	15
Drought	1.270138		15
Groups	*Variance*	*P-value*	*Count*
Waterlogged	0.858857	0.631012	15
Control	2.318188		15
Groups	*Variance*	*P-value*	*Count*
Drought	1.270138	0.000696	15
Waterlogged	0.858857		15

Wavelength 2216 nm Alpha= 0.05

Groups	*Variance*	*P-value*	*Count*
Control	1.573605	0.006748	15
Drought	1.266633		15
Groups	*Variance*	*P-value*	*Count*
Waterlogged	0.804063	0.821258	15
Control	1.573605		15
Groups	*Variance*	*P-value*	*Count*
Drought	1.266633	0.002018	15
Waterlogged	0.804063		15

28/02/2004	Control	Waterlogged	Drought
RWC (%)	68.4	58.4	49.0

Wavelength 1666 nm Alpha= 0.05

Groups	*Variance*	*P-value*	*Count*
Control	2.917258	0.000453	15
Drought	0.284507		15
Groups	*Variance*	*P-value*	*Count*
Waterlogged	2.626513	0.292296	15
Control	2.917258		15
Groups	*Variance*	*P-value*	*Count*
Drought	0.284507	0.002209	15
Waterlogged	2.626513		15

Wavelength 2216 nm Alpha= 0.05

Groups	*Variance*	*P-value*	*Count*
Control	2.020567	0.00131	15
Drought	0.83727		15
Groups	*Variance*	*P-value*	*Count*
Waterlogged	2.02532	0.477369	15
Control	2.020567		15
Groups	*Variance*	*P-value*	*Count*
Drought	0.83727	0.004317	15
Waterlogged	2.02532		15

APPENDIX 1-5: ONE-WAY ANOVA TEST FOR MICRONUTRIENT STRESS STUDY

Date: 5/03/2004

Absorption Hull	468 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0000492	0.196524	15
SC-All MN	0.0017521		15
Absorption Hull	674 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.000544	0.24672	15
SC-All MN	0.0056175		15
Absorption Hull	1466 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0009206	0.78669	15
SC-All MN	0.0004273		15
Absorption Hull	1944 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0012612	0.915345	15
SC-All MN	0.0093579		15

Absorption Trough	560 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0049942	0.055163	15
SC-All MN	0.0016595		15
Absorption Trough	892 nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0000781	0.322539	15
SC-All MN	0.0000205		15
Absorption Trough	2230nm		Alpha= 0.05
Groups	*Variance*	*P-value*	*Count*
SC-Low MN	0.0016452	0.907094	15
SC-All MN	0.0001031		15

APPENDIX 1-6: Z-TEST FOR ANNUAL RYEGRASS WITH ALL NUTRIENTS AND LOW NUTRIENTS

Z-Test: Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.619491619	0.618764095
Known Variance	0.1257	0.1309
Observations	1050	1050
Hypothesized Mean Difference	0	
z	0.046538624	
P(Z<=z) one-tail	0.481440409	
z Critical one-tail	1.644853	
P(Z<=z) two-tail	0.962880818	
z Critical two-tail	1.959961082	

APPENDIX 2-1 ET_O FOR DUMBLEYUNG AND NAREMBEEN

Country : Australia Station : Dumbleyung

Altitude: 270 meter(s) above M.S.L.

Latitude: -33.19 Deg. (South) Longitude: 117.44 Deg. (East)

Month	MaxTemp (deg.C)	MiniTemp (deg.C)	Humidity (%)	Wind Spd. (Km/d)	SunShine (Hours)	Solar Rad. (MJ/m2/d)	ETo (mm/d)
January	31.0	14.4	42.5	384.0	11.7	28.9	8.68
February	29.9	14.7	46.0	342.0	11.1	26.4	7.54
March	27.6	13.3	50.0	344.0	9.5	21.2	6.14
April	23.7	10.6	57.0	284.0	8.1	15.7	4.07
May	19.4	8.0	68.0	307.0	6.7	11.2	2.66
June	16.2	6.2	74.0	285.0	5.8	9.1	1.85
July	15.3	5.7	74.5	304.0	5.9	9.7	1.88
August	15.8	5.6	71.5	335.0	7.2	13.4	2.49
September	18.1	6.2	64.5	351.0	7.7	17.3	3.58
October	21.5	7.6	53.0	388.0	9.7	23.2	5.39
November	25.4	10.5	46.5	381.0	10.6	26.7	6.93
December	29.2	12.9	42.0	377.0	11.8	29.4	8.32
Average	22.8	9.6	57.5	340.2	8.8	19.4	4.96

Pen-Mon equation was used in ETo calculations with the following values for Angstrom's Coefficients: a = 0.25 b = 0.5

Country : Australia Station : Narembeen

Altitude: 276 meter(s) above M.S.L.

Latitude: -32.06 Deg. (South) Longitude: 118.40 Deg. (East)

Month	MaxTemp (deg.C)	MiniTemp (deg.C)	Humidity (%)	Wind Spd. (Km/d)	SunShine (Hours)	Solar Rad. (MJ/m2/d)	ETo (mm/d)
January	33.7	16.5	38.0	377.0	11.7	29.0	9.51
February	32.7	16.5	42.5	342.0	11.1	26.6	8.32
March	30.0	14.5	44.5	335.0	9.5	21.5	6.83
April	25.7	12.1	56.5	282.0	8.1	16.0	4.40
May	20.8	8.2	67.0	253.0	6.7	11.5	2.69
June	17.4	6.4	74.0	257.0	5.8	9.4	1.93
July	16.5	5.5	72.0	265.0	5.9	10.0	2.03
August	17.4	5.2	68.5	268.0	7.2	13.7	2.65
September	20.3	6.1	61.5	273.0	7.7	17.5	3.79
October	24.7	9.0	47.5	319.0	9.7	23.3	5.93
November	28.1	12.0	41.0	339.0	10.6	26.8	7.51
December	31.9	14.5	38.5	330.0	11.8	29.5	8.73
Average	24.9	10.5	54.3	303.3	8.8	19.6	5.36

Pen-Mon equation was used in ETo calculations with the following values for Angstrom's Coefficients: a = 0.25 b = 0.5

APPENDIX 2-2 WATERTABLE DEPTHS IN MONITORING BORES AT BEYNON ROAD IN DUMBLEYUNG

Bore No	Easting	Northing	Highest GWL in 2002	Lowest GWL in 2003	Highest GWL in 2003	Recovery in 2003	Drawdown in 2003	Lowest GWL in 2004	Highest GWL in 2004	Recovery in 2004	Drawdown in 2004	Lowest GWL in 2005	Highest GWL in 2005	Recovery in 2005	Drawdown in 2005
DD01-D	575151	6324318	282.2	280.5	281.1	0.6	1.7	280.4	280.8	0.4	0.3	280.6	280.9	0.3	0.1
DD01-OB	575151	6324342	281.9	280.5	280.9	0.4	1.4	280.4	280.8	0.4	0.3	280.6	280.1	-0.6	-0.8
DD02-OB	575217	6324322	282.0	280.7	281.3	0.6	1.3	280.7	280.9	0.2	0.2	280.9	281.4	0.5	0.5
DD03-S	575101	6324320	281.9	280.5	280.8	0.3	1.4	280.4	280.7	0.3	0.2	280.5	280.8	0.3	0.1
DD04-S	575085	6324325	282.0	280.4	280.7	0.4	1.7	280.4	280.6	0.2	0.2	280.5	280.7	0.2	0.1
DD05-I	575063	6324325	282.0	-	280.6	-	-	-	-	-	-	-	-	-	-
DD05-S	575063	6324320	282.0	-	281.9	-	-	-	-	-	-	-	-	-	-
DD06-S	575041	6324329	282.0	-	-	-	-	-	-	-	-	-	-	-	-
DD07-S	575004	6324322	282.2	-	-	-	-	-	-	-	-	-	-	-	-
DD08-S	574919	6324329	283.1	-	-	-	-	-	-	-	-	-	-	-	-
DD25-OB	574914	6324245	282.2	280.8	281.3	0.5	1.4	280.7	281.1	0.4	0.3	281.0	281.5	0.5	0.4
DD26-OB	574959	6324199	281.9	280.5	281.0	0.5	1.4	280.4	280.8	0.4	0.3	280.5	281.9	1.4	1.1
DD27-OB	574997	6324157	281.9	280.3	280.8	0.5	1.6	280.2	280.6	0.4	0.4	280.5	280.9	0.4	0.3
DD28-OB	575037	6324121	281.8	280.3	280.9	0.5	1.5	280.2	280.1	-0.2	-0.3	280.5	280.9	0.4	0.9
DD29-OB	575071	6324096	281.7	280.3	280.9	0.6	1.4	280.2	280.6	0.4	0.3	280.5	281.0	0.4	0.3
DD30-OB	575075	6324058	281.7	280.4	280.9	0.6	1.3	280.2	280.6	0.4	0.2	280.4	280.9	0.6	0.3
DD31-OB	575103	6324023	281.6	280.3	280.9	0.6	1.3	280.1	280.6	0.6	0.3	280.5	281.0	0.5	0.3
DD32-OB	575129	6323994	281.6	280.3	281.1	0.8	1.2	280.2	280.7	0.5	0.4	280.5	281.8	1.3	1.1
DD33-OB	575148	6323973	281.5	280.4	280.9	0.5	1.1	280.2	280.6	0.4	0.2	280.5	280.9	0.4	0.3
DD34-OB	575176	6323930	281.2	280.3	280.9	0.6	0.9	280.1	280.6	0.5	0.3	280.4	280.9	0.5	0.3
DD35-OB	575211	6323900	281.3	280.3	280.9	0.6	1.0	280.1	280.6	0.5	0.3	280.3	280.9	0.7	0.3
DD36-OB	575252	6323866	281.2	280.3	281.0	0.7	0.9	280.0	281.0	0.9	0.6	280.3	280.8	0.5	-0.1
DD37-OB	575310	6324157	281.6	280.2	280.6	0.4	1.5	280.0	280.5	0.4	0.3	280.4	280.7	0.3	0.2
DD38-OB	575346	6324191	281.8	280.6	281.3	0.7	1.2	280.6	281.0	0.4	0.4	280.8	281.4	0.5	0.4
DD39-OB	575383	6324219	281.2	280.2	281.4	1.2	1.0	280.1	281.2	1.1	1.1	281.1	281.5	0.4	0.3
DD40-OB	575424	6324258	282.0	281.2	281.6	0.5	0.8	281.1	281.5	0.4	0.3	281.2	281.7	0.5	0.2
DD41-OB	575450	6323984	281.4	280.2	280.7	0.5	1.2	280.1	280.6	0.5	0.4	280.4	280.8	0.4	0.2
DD42-OB	575490	6324015	281.4	280.4	281.0	0.6	1.0	280.4	280.9	0.5	0.4	280.7	281.1	0.4	0.3
DD43-OB	575526	6324044	281.5	280.4	281.2	0.8	1.1	280.6	281.0	0.5	0.6	281.0	281.4	0.4	0.4
DD44-OB	575575	6324068	281.6	280.9	281.4	0.4	0.6	280.8	281.2	0.5	0.3	281.0	281.6	0.6	0.4
DD45-OB	575653	6324123	281.7	281.0	281.8	0.7	0.7	280.0	281.5	1.5	0.5	281.1	281.8	0.7	0.3
		Mean	281.8	280.5	281.1	0.6	1.2	280.3	280.8	0.5	0.3	280.6	281.1	0.5	0.3
		Max	283.1	281.2	281.9	1.2	1.7	281.1	281.5	1.5	1.1	281.2	281.9	1.4	1.1
		Min	281.2	280.2	280.6	0.3	0.6	280.0	280.1	-0.2	-0.3	280.3	280.1	-0.6	-0.8

APPENDIX 2-3 WATERTABLE DEPTHS IN MONITORING BORES AT TEMBY ROAD IN DUMBLEYUNG

Site	Easting	Northing	Highest GWL in 2002	Lowest GWL in 2003	Highest GWL in 2003	Drawdown in 2003	Recovery in 2003	Lowest GWL in 2004	Highest GWL in 2004	Recovery in 2004	Drawdown in 2004	Lowest GWL in 2005	Highest GWL in 2005	Recovery in 2005	Drawdown in 2005
DD19-0B	565872	6327749	302.4	301.6	302.1	0.9	0.6	301.6	302.2	0.6	0.6	301.8	302.4	0.6	0.2
DD20-0B	565893	6327749	301.8	301.5	302.5	0.3	1.1	301.4	302.2	0.8	0.7	301.7	302.2	0.5	0.0
DD21-0B	565936	6327766	301.6	301.4	302.0	0.2	0.5	301.4	302.1	0.7	0.7	301.6	302.3	0.7	0.2
		Mean	301.9	301.5	302.2	0.5	0.7	301.5	302.2	0.7	0.7	301.7	302.3	0.6	0.1
		Max	302.4	301.6	302.5	0.9	1.1	301.6	302.2	0.8	0.7	301.8	302.4	0.7	0.2
		Min	301.6	301.4	302.0	0.2	0.5	301.4	302.1	0.6	0.6	301.6	302.2	0.5	0.0

APPENDIX 2-4 WATERTABLE DEPTHS IN MONITORING BORES AT MOUNT PLEASANT ROAD IN DUMBLEYUNG

Site	Easting	Northing	Highest GWL in 2002	Lowest GWL in 2003	Highest GWL in 2003	Drawdown in 2003	Recovery in 2003	Lowest GWL in 2004	Highest GWL in 2004	Recovery in 2004	Drawdown in 2004	Lowest GWL in 2005	Highest GWL in 2005	Recovery in 2005	Drawdown in 2005
DD22-OB	568644	6323925	292.5	292.3	292.8	0.2	0.5	292.3	292.8	0.5	0.6	292.3	292.7	0.4	-0.1
DD23-0B	568625	6323944	292.3	292.3	292.7	0.0	0.4	292.4	292.8	0.4	0.5	292.3	292.7	0.4	-0.1
DD23-I	568622	6323946	292.8	292.5	292.9	0.3	0.4	292.6	293.1	0.4	0.5	292.7	293.0	0.3	-0.1
DD24-0B	568601	6323947	292.5	292.1	292.5	0.4	0.4	292.4	292.8	0.4	0.3	292.1	292.4	0.3	0.0
		Mean	292.5	292.3	292.7	0.2	0.4	292.4	292.9	0.4	0.5	292.3	292.7	0.3	-0.1
		Max	292.8	292.5	292.9	0.4	0.5	292.6	293.1	0.5	0.6	292.7	293.0	0.4	0.0
		Min	292.3	292.1	292.5	0.0	0.4	292.3	292.8	0.4	0.3	292.1	292.4	0.3	-0.1

APPENDIX 3-1 STATISTICS FOR KELLERBERIN LANDSAT IMAGES

STATISTICS FOR DAT ASET: KEL10A UG1989_CAL.ERS

REGION: All

	Band1	Band2	Band3	Band4	Band5	Band6
	-----	-----	-----	-----	-----	-----
Null Cells	25723749	25723584	25723518	25723346	25729030	25774119
Non-Null Cells	51201587	51201752	51201818	51201990	51196306	51151217
Area In Hectares	3200099.188	3200110	3200113	625 3200124	.375 319976	9.125 3196951.063
Area In Acres	7907617.898	7907643	7907653	574 7907680	.137 790680	2.295 7899838.711
Minimum	2	2	11	9	17	11
Maximum	255	255	255	255	255	255
Mean	98.353	48.176	63.337	93.549	133.7	63.787
Median	97	46	60	95	130	61
Std. Dev.	11.069	9.006	16.548	20.987	33.171	21.399
Std. Dev. (n-1)	11.069	9.006	16.548	20.987	33.171	21.399
Corr. Eigenval.	4.424	0.966	0.453	0.104	0.029	0.024
Cov. Eigenval.	1901.95	416.22	120.273	17.984	16.763	2.945

Correlation Matrix	Band1	Band2	Band3	Band4	Band5	Band6
------------------	-----	-----	-----	-----	-----	-----
Band1	1	0.923	0.88	0.19	0.714	0.728
Band2	0.923	1	0.948	0.296	0.791	0.779
Band3	0.88	0.948	1	0.135	0.817	0.841
Band4	0.19	0.296	0.135	1	0.339	0.152
Band5	0.714	0.791	0.817	0.339	1	0.954
Band6	0.728	0.779	0.841	0.152	0.954	1
Determinant	0					

Corr. Eigenvectors	PC1	PC2	PC3	PC4	PC5	PC6
------------------	-----	-----	-----	-----	-----	-----
Band1	0.431	0.105	0.502	-0.711	0.133	0.168
Band2	0.454	0.002	0.368	0.313	-0.556	-0.501
Band3	0.454	0.173	0.17	0.601	0.467	0.395
Band4	0.144	-0.968	0.065	0.02	0.191	-0.025
Band5	0.438	-0.085	-0.532	-0.097	-0.504	0.505
Band6	0.435	0.119	-0.545	-0.159	0.407	-0.556

Inv. of Corr. Ev.	PC1	PC2	PC3	PC4	PC5	PC6
-----------------	-----	-----	-----	-----	-----	-----
Band1	0.431	0.454	0.454	0.144	0.438	0.435
Band2	0.105	0.002	0.173	-0.968	-0.085	0.119
Band3	0.502	0.368	0.17	0.065	-0.532	-0.545
Band4	-0.711	0.313	0.601	0.02	-0.097	-0.159
Band5	0.133	-0.556	0.467	0.191	-0.504	0.407
Band6	0.168	-0.501	0.395	-0.025	0.505	-0.556

Covariance Matrix	Band1	Band2	Band3	Band4	Band5	Band6
-----------------	-----	-----	-----	-----	-----	-----
Band1	122.532	92.003	161.174	44.19	262.029	172.534
Band2	92.003	81.101	141.255	55.908	236.381	150.049
Band3	161.174	141.255	273.829	47.04	448.35	297.879
Band4	44.19	55.908	47.04	440.454	236.169	68.13
Band5	262.029	236.381	448.35	236.169	1100.285	677.306
Band6	172.534	150.049	297.879	68.13	677.306	457.933
Determinant	84523084330	0.784				

Cov. Eigenvectors	PC1	PC2	PC3	PC4	PC5	PC6
-----------------	-----	-----	-----	-----	-----	-----
Band1	0.2	0.064	0.528	-0.734	0.267	-0.259
Band2	0.178	0.013	0.392	0.039	0.066	0.899
Band3	0.334	0.167	0.599	0.594	-0.175	-0.343
Band4	0.167	-0.962	0.104	-0.01	-0.18	-0.051
Band5	0.752	-0.008	-0.393	0.116	0.515	-0.02
Band6	0.472	0.204	-0.206	-0.306	-0.772	0.064

Inv. of Cov. Ev.	PC1	PC2	PC3	PC4	PC5	PC6
----------------	-----	-----	-----	-----	-----	-----
Band1	0.2	0.178	0.334	0.167	0.752	0.472
Band2	0.064	0.013	0.167	-0.962	-0.008	0.204
Band3	0.528	0.392	0.599	0.104	-0.393	-0.206
Band4	-0.734	0.039	0.594	-0.01	0.116	-0.306
Band5	0.267	0.066	-0.175	-0.18	0.515	-0.772
Band6	-0.259	0.899	-0.343	-0.051	-0.02	0.064

ASET: KELSEP 1990_CAL.ERS

STATISTICS FOR DAT

REGION: All

	Band1	Band2	Band3	Band4	Band5	Band6
	-----	-----	-----	-----	-----	-----
Null Cells	27061504	27061943	27061815	27061586	27062365	27137953
Non-Null Cells	51430376	51429937	51430065	51430294	51429515	51353927
Area In Hectares	3214398.5	3214371	3214379	063 3214393	.375 321434	4.688 3209620.438
Area In Acres	7942952.271	7942884	7942904	240 7942939	.607 794281	9.297 7931145.421
Minimum	13	6	12	8	17	10
Maximum	255	197	255	205	255	255
Mean	98.219	47.421	64.238	89.709	131.254	64.216
Median	96	46	62	90	131	64
Std. Dev.	11.779	8.967	16.245	18.167	27.098	18.934
Std. Dev. (n-1)	11.779	8.967	16.245	18.167	27.098	18.934
Corr. Eigenval.	4.189	1.029	0.626	0.108	0.029	0.019
Cov. Eigenval.	1376.643	335.647	158.952	19.652	12.799	2.218

Correlation Matrix	Band1	Band2	Band3	Band4	Band5	Band6
------------------	-----	-----	-----	-----	-----	-----
Band1	1	0.927	0.876	0.136	0.635	0.631

Band2	**0.927**	**1**	**0.953**	**0.24**	**0.716**	**0.677**
Band3	**0.876**	**0.953**	**1**	**0.084**	**0.769**	**0.765**
Band4	**0.136**	**0.24**	**0.084**	**1**	**0.167**	**-0.023**
Band5	**0.635**	**0.716**	**0.769**	**0.167**	**1**	**0.954**
Band6	**0.631**	**0.677**	**0.765**	**-0.023**	**0.954**	**1**
Determinant	**0**					

Corr. Eigenvectors	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
------------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.437**	**-0.047**	**0.472**	**-0.725**	**-0.056**	**0.234**
Band2	**0.461**	**-0.128**	**0.34**	**0.26**	**0.334**	**-0.69**
Band3	**0.467**	**0.052**	**0.233**	**0.616**	**-0.305**	**0.502**
Band4	**0.085**	**-0.954**	**-0.228**	**-0.011**	**-0.173**	**0.034**
Band5	**0.435**	**0.065**	**-0.549**	**-0.053**	**0.643**	**0.299**
Band6	**0.426**	**0.254**	**-0.503**	**-0.157**	**-0.592**	**-0.356**

Inv. of Corr. Ev.	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.437**	**0.461**	**0.467**	**0.085**	**0.435**	**0.426**
Band2	**-0.047**	**-0.128**	**0.052**	**-0.954**	**0.065**	**0.254**
Band3	**0.472**	**0.34**	**0.233**	**-0.228**	**-0.549**	**-0.503**
Band4	**-0.725**	**0.26**	**0.616**	**-0.011**	**-0.053**	**-0.157**
Band5	**-0.056**	**0.334**	**-0.305**	**-0.173**	**0.643**	**-0.592**
Band6	**0.234**	**-0.69**	**0.502**	**0.034**	**0.299**	**-0.356**

Covariance Matrix	**Band1**	**Band2**	**Band3**	**Band4**	**Band5**	**Band6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**138.734**	**97.917**	**167.711**	**29.097**	**202.829**	**140.629**
Band2	**97.917**	**80.402**	**138.862**	**39.066**	**173.878**	**114.92**
Band3	**167.711**	**138.862**	**263.903**	**24.775**	**338.382**	**235.366**
Band4	**29.097**	**39.066**	**24.775**	**330.054**	**82.253**	**-7.832**
Band5	**202.829**	**173.878**	**338.382**	**82.253**	**734.321**	**489.618**
Band6	**140.629**	**114.92**	**235.366**	**-7.832**	**489.618**	**358.496**
Determinant	**40969230855**	**0.522**				

Cov. Eigenvectors	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.242**	**-0.031**	**0.539**	**0.759**	**0.12**	**0.245**
Band2	**0.201**	**-0.068**	**0.367**	**-0.05**	**0.083**	**-0.9**
Band3	**0.384**	**0.028**	**0.577**	**-0.622**	**-0.123**	**0.342**
Band4	**0.076**	**-0.978**	**-0.07**	**-0.002**	**-0.176**	**0.047**
Band5	**0.714**	**-0.013**	**-0.418**	**-0.034**	**0.559**	**0.043**
Band6	**0.488**	**0.193**	**-0.25**	**0.183**	**-0.788**	**-0.091**

Inv. of Cov. Ev.	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.242**	**0.201**	**0.384**	**0.076**	**0.714**	**0.488**
Band2	**-0.031**	**-0.068**	**0.028**	**-0.978**	**-0.013**	**0.193**
Band3	**0.539**	**0.367**	**0.577**	**-0.07**	**-0.418**	**-0.25**
Band4	**0.759**	**-0.05**	**-0.622**	**-0.002**	**-0.034**	**0.183**
Band5	**0.12**	**0.083**	**-0.123**	**-0.176**	**0.559**	**-0.788**
Band6	**0.245**	**-0.9**	**0.342**	**0.047**	**0.043**	**-0.091**

ASET: KEL23S EP1993_CAL.ERS

STATISTICS FOR DAT

REGION: All

	Band1	Band2	Band3	Band4	Band5	Band6
	-----	-----	-----	-----	-----	-----
Null Cells	24187047	24187514	24187151	24186887	24187794	24191054
Non-Null Cells	51580953	51580486	51580849	51581113	51580206	51576946
Area In Hectares	3223810	3223780	3223803	063 3223819	.563 322376	2.875 3223559.125
Area In Acres	7966208	7966135	7966191	453 7966232	.225 796609	2.147 7965588.670
Minimum	6	6	9	7	13	9
Maximum	255	198	219	188	215	255
Mean	92.189	44.952	57.389	94.658	113.718	51.488
Median	90	43	55	95	112	49
Std. Dev.	11.337	8.405	15.977	22.05	24.842	16.024
Std. Dev. (n-1)	11.337	8.405	15.977	22.05	24.842	16.024
Corr. Eigenval.	3.874	1.149	0.81	0.109	0.034	0.024
Cov. Eigenval.	1102.479	478.937	201.806	17.294	11.163	2.829

Correlation Matrix	Band1	Band2	Band3	Band4	Band5	Band6
------------------	-----	-----	-----	-----	-----	-----
Band1	1	0.904	0.857	-0.05	0.46	0.477
Band2	0.904	1	0.936	0.055	0.572	0.548
Band3	0.857	0.936	1	-0.153	0.694	0.714
Band4	-0.05	0.055	-0.153	1	-0.084	-0.277
Band5	0.46	0.572	0.694	-0.084	1	0.949
Band6	0.477	0.548	0.714	-0.277	0.949	1
Determinant	0					

Corr. Eigenvectors	PC1	PC2	PC3	PC4	PC5	PC6
------------------	-----	-----	-----	-----	-----	-----
Band1	0.43	-0.299	0.386	-0.749	0.022	0.125
Band2	0.458	-0.331	0.195	0.387	-0.401	-0.576
Band3	0.489	-0.086	0.168	0.504	0.428	0.536
Band4	-0.078	-0.771	-0.6	-0.038	0.193	0.018
Band5	0.421	0.24	-0.534	-0.085	-0.582	0.366
Band6	0.427	0.376	-0.374	-0.163	0.528	-0.481

Inv. of Corr. Ev.	PC1	PC2	PC3	PC4	PC5	PC6
-----------------	-----	-----	-----	-----	-----	-----
Band1	0.43	0.458	0.489	-0.078	0.421	0.427
Band2	-0.299	-0.331	-0.086	-0.771	0.24	0.376
Band3	0.386	0.195	0.168	-0.6	-0.534	-0.374
Band4	-0.749	0.387	0.504	-0.038	-0.085	-0.163
Band5	0.022	-0.401	0.428	0.193	-0.582	0.528
Band6	0.125	-0.576	0.536	0.018	0.366	-0.481

Covariance Matrix	Band1	Band2	Band3	Band4	Band5	Band6
-----------------	-----	-----	-----	-----	-----	-----
Band1	128.526	86.1	155.292	-12.491	129.51	86.618
Band2	86.1	70.639	125.654	10.226	119.424	73.84
Band3	155.292	125.654	255.278	-54.028	275.451	182.779
Band4	-12.491	10.226	-54.028	486.188	-46.029	-97.837
Band5	129.51	119.424	275.451	-46.029	617.123	377.664
Band6	86.618	73.84	182.779	-97.837	377.664	256.754
Determinant	5.82E+10	0.729				

Cov. Eigenvectors	PC1	PC2	PC3	PC4	PC5	PC6
-----------------	-----	-----	-----	-----	-----	-----
Band1	0.22	-0.067	0.557	-0.778	0.02	-0.176
Band2	0.182	-0.098	0.363	0.122	0.137	0.889
Band3	0.41	-0.05	0.555	0.604	-0.057	-0.391
Band4	-0.164	-0.976	-0.033	0.02	-0.132	-0.043
Band5	0.713	-0.173	-0.443	-0.076	0.507	-0.052
Band6	0.464	0.035	-0.228	-0.089	-0.838	0.144

Inv. of Cov. Ev.	PC1	PC2	PC3	PC4	PC5	PC6
----------------	-----	-----	-----	-----	-----	-----
Band1	0.22	0.182	0.41	-0.164	0.713	0.464
Band2	-0.067	-0.098	-0.05	-0.976	-0.173	0.035
Band3	0.557	0.363	0.555	-0.033	-0.443	-0.228
Band4	-0.778	0.122	0.604	0.02	-0.076	-0.089
Band5	0.02	0.137	-0.057	-0.132	0.507	-0.838
Band6	-0.176	0.889	-0.391	-0.043	-0.052	0.144

STATISTICS FOR DAT ASET: KEL08A UG94.ERS

REGION: All

	Band1	Band2	Band3	Band4	Band5	Band6
	-----	-----	-----	-----	-----	-----
Null Cells	22843091	22842342	22839351	22839046	22839536	22839676
Non-Null Cells	51654989	51655738	51658729	51659034	51658544	51658404
Area In Hectares	3228437	3228484	3228670	563 3228689	.625 322865	9.000 3228650.250
Area In Acres	7977642	7977757	7978219	308 7978266	.413 797819	0.737 7978169.115
Minimum	2	2	1	1	13	5
Maximum	255	249	255	254	255	255
Mean	98.874	48.019	61.064	92.555	137.444	65.723
Median	98	46	57	94	136	64
Std. Dev.	11.55	8.784	16.881	21.436	30.304	19.7
Std. Dev. (n-1)	11.55	8.784	16.881	21.436	30.304	19.7
Corr. Eigenval.	4.306	0.964	0.544	0.119	0.037	0.03
Cov. Eigenval.	1649.081	426.696	142.301	22.212	17.464	3.705

Correlation Matrix	Band1	Band2	Band3	Band4	Band5	Band6
------------------	-----	-----	-----	-----	-----	-----
Band1	1	0.908	0.856	0.22	0.661	0.667
Band2	0.908	1	0.927	0.346	0.759	0.73
Band3	0.856	0.927	1	0.133	0.775	0.805
Band4	0.22	0.346	0.133	1	0.375	0.157

Band5	**0.661**	**0.759**	**0.775**	**0.375**	**1**	**0.942**
Band6	**0.667**	**0.73**	**0.805**	**0.157**	**0.942**	**1**
Determinant	**0**					

Corr. Eigenvectors	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
------------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.428**	**0.105**	**0.507**	**-0.708**	**0.17**	**0.135**
Band2	**0.457**	**-0.016**	**0.358**	**0.3**	**-0.648**	**-0.391**
Band3	**0.453**	**0.216**	**0.172**	**0.608**	**0.513**	**0.293**
Band4	**0.165**	**-0.955**	**0.056**	**0.04**	**0.228**	**-0.064**
Band5	**0.438**	**-0.093**	**-0.525**	**-0.104**	**-0.391**	**0.601**
Band6	**0.43**	**0.145**	**-0.554**	**-0.163**	**0.289**	**-0.614**

Inv. of Corr. Ev.	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.428**	**0.457**	**0.453**	**0.165**	**0.438**	**0.43**
Band2	**0.105**	**-0.016**	**0.216**	**-0.955**	**-0.093**	**0.145**
Band3	**0.507**	**0.358**	**0.172**	**0.056**	**-0.525**	**-0.554**
Band4	**-0.708**	**0.3**	**0.608**	**0.04**	**-0.104**	**-0.163**
Band5	**0.17**	**-0.648**	**0.513**	**0.228**	**-0.391**	**0.289**
Band6	**0.135**	**-0.391**	**0.293**	**-0.064**	**0.601**	**-0.614**

Covariance Matrix	**Band1**	**Band2**	**Band3**	**Band4**	**Band5**	**Band6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**133.397**	**92.098**	**166.919**	**54.353**	**231.219**	**151.736**
Band2	**92.098**	**77.158**	**137.402**	**65.14**	**201.973**	**126.282**
Band3	**166.919**	**137.402**	**284.974**	**48.299**	**396.226**	**267.566**
Band4	**54.353**	**65.14**	**48.299**	**459.516**	**243.43**	**66.506**
Band5	**231.219**	**201.973**	**396.226**	**243.43**	**918.315**	**562.17**
Band6	**151.736**	**126.282**	**267.566**	**66.506**	**562.17**	**388.098**
Determinant	**1.44E+10**	**7.498**				

Cov. Eigenvectors	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
-----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.216**	**0.069**	**0.538**	**-0.773**	**0.008**	**-0.25**
Band2	**0.184**	**0.009**	**0.359**	**0.008**	**0.08**	**0.912**
Band3	**0.356**	**0.21**	**0.584**	**0.625**	**0.014**	**-0.31**
Band4	**0.21**	**-0.949**	**0.111**	**0.07**	**-0.186**	**-0.061**
Band5	**0.734**	**0.007**	**-0.411**	**-0.064**	**0.536**	**-0.032**
Band6	**0.458**	**0.225**	**-0.243**	**-0.054**	**-0.82**	**0.073**

Inv. of Cov. Ev.	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
----------------	**-----**	**-----**	**-----**	**-----**	**-----**	**-----**
Band1	**0.216**	**0.184**	**0.356**	**0.21**	**0.734**	**0.458**
Band2	**0.069**	**0.009**	**0.21**	**-0.949**	**0.007**	**0.225**
Band3	**0.538**	**0.359**	**0.584**	**0.111**	**-0.411**	**-0.243**
Band4	**-0.773**	**0.008**	**0.625**	**0.07**	**-0.064**	**-0.054**
Band5	**0.008**	**0.08**	**0.014**	**-0.186**	**0.536**	**-0.82**
Band6	**-0.25**	**0.912**	**-0.31**	**-0.061**	**-0.032**	**0.073**

APPENDIX 5-1 HIGHEST DAILY RAINFALL OF STATIONS WITH DATES AND PERIODS OF RECORD FOR WESTERN AUSTRALIA

City	Eastings	Northings	Highest Daily Rainfall (mm)	Date	Period
Albany	580,348	6,123,384	104	6 May 1921	1877-2007
Broome Airport	1,055,018	8,007,787	477	30 January 1997	1939-2008
Bakers Hill	450,575	6,486,002	69	11 May 1987	1964-2007
Brookton	500,677	6,418,262	91	16 March 1963	1907-2008
Bunbury	373,900	6,308,335	92	4 July 1999	1995-2008
Bunbury P.O.	372,489	6,311,644	115	22 January 1982	1877-1985
Busselton Shire	346,607	6,274,179	142	21 May 1991	1877-2007
Carnarvon	767,690	7,243,508	96	27 June 1965	1965-2006
Collie	420,910	6,309,576	118	21 January 1982	1899-2008
Coorow	405,686	6,693,889	127	14 April 1961	1912-2005
Corrigin	582,193	6,422,727	146	13 January 2006	1910-2008
Cue	588,900	6,966,347	119	22 February 1975	1894-2008
Dalwallinu Comparison	467,482	6,650,438	112	28 March, 1971	1912-2008
Dampier Salt	473,794	7,707,949	195	10 January 2006	1969-2008
Denham	753,597	7,130,039	182	18 February, 2008	1893-2008
Donnybrook	390,919	6,284,678	126	9 April 1985	1907-2008
Dumbleyung	568,883	6,313,623	119	17 February 1955	1889-2004
Eneabba	333,041	6,700,085	78	7 February 2008	1964-2007
Esperence	952,922	6,245,898	126	30 April 1922	1896-1969
Esperence Downs Res. St.	943,928	6,271,568	152	5 January 2007	1951-2008
Eyre	1,377,826	6,394,020	76	17 March 2000	1888-2008
Geraldton A.P.	275,263	6,812,506	109	13 June 1945	1941-2008
Geraldton Port	265,866	6,814,483	94	8 March 1934	1877-2007
Hyden	678,454	6,408,983	100	2 January 1966	1928-2007
Kalgoorlie P.O.	927736.42	6589556.4	178	22 February 1948	1896-1953
Kalgoorlie-Boulder A.P.	926298.55	6585756.6	178	22 February 1948	1939-2008
Karratha Aero	476,488	7,709,956	212	10 January 2006	1972-2008
Katanning	556,206	6,272,525	126	17 February 1955	1891-2008
Kellerberrin	568,450	6,501,633	108	14 May 1939	1894-2007
Kimberley Res. Station	1,762,433	8,234,096	431	6 April 1959	1944-2008
Kojonup	514,713	6,256,669	114	21 January 1982	1885-2007
Kununurra	1,764,469	8,219,508	134	3 February 1969	1962-1997
Kununurra Aero	1,761,719	8,219,822	162	2 January 2005	1971-2008
Kuri Bay	1,308,835	8,273,511	505	17 January 1982	1961-2008

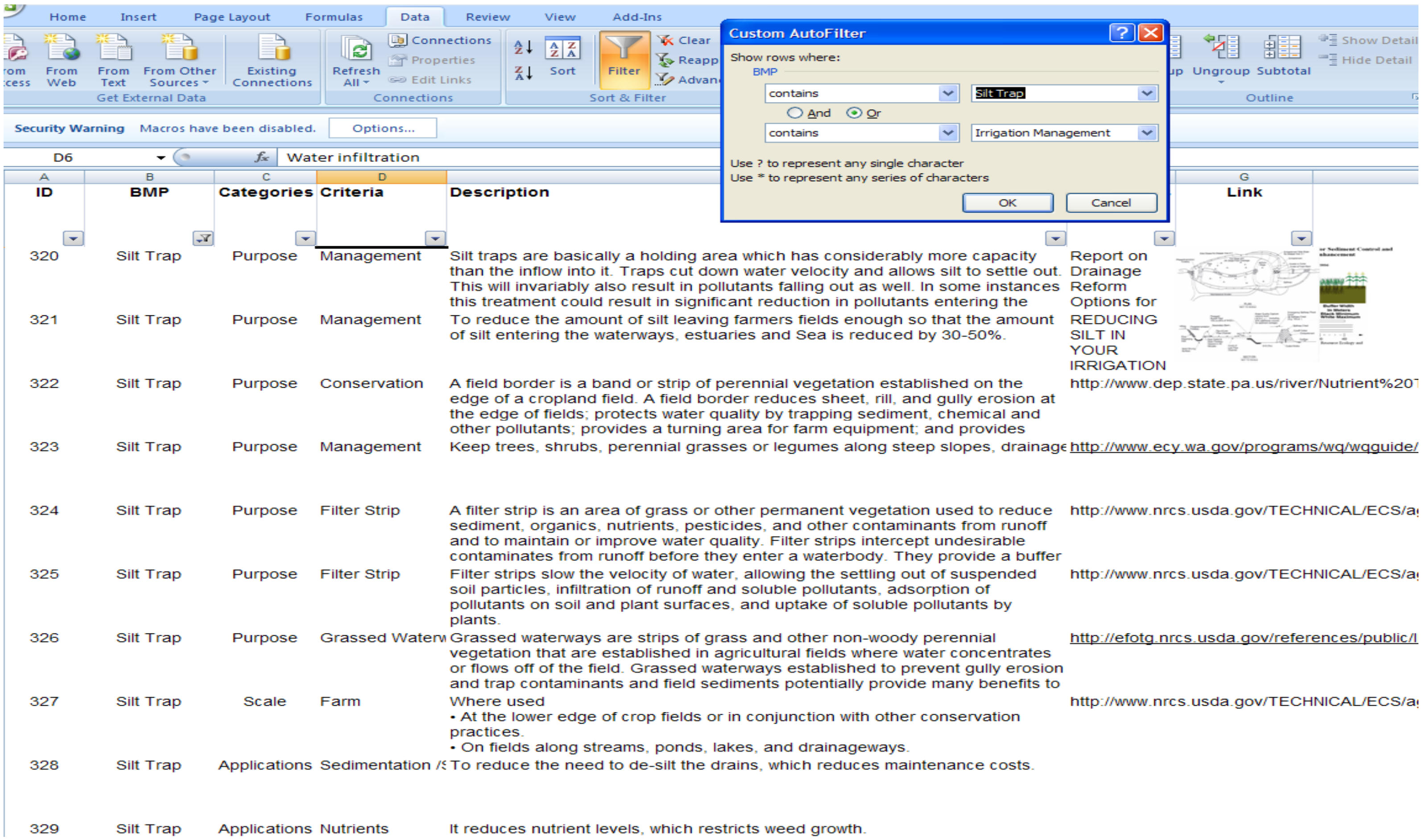
APPENDIX 5-1 (CONTINUED) HIGHEST DAILY RAINFALL OF STATIONS WITH DATES AND PERIODS OF RECORD FOR WESTERN AUSTRALIA

City	Eastings	Northings	Highest Daily Rainfall (mm)	Date	Period
Lake Grace Comparison	636,472	6,336,596	130	29 January 1990	1912-2008
Mandurah Park	384,116	6,403,114	144	21 January 1982	1907-2001
Manjimup	421,274	6,209,691	89	26 March 1965	1916-2008
Marble Bar Comparison	785,520	7,655,934	305	2 March 1941	1895-2006
Merredin	621,486	6,516,968	83	19 March 1917	1904-2008
Moora	404,866	6,609,674	143	16 February 1955	1897-2004
Mt. Magnet	583,558	6,895,638	113	22 February 1975	1895-2008
Mullewa	354,633	6,842,431	138	28 February 1994	1896-2008
Muresk Ag C	470,005	6,487,219	128	9 March 1934	1926-1981
Narembeen	631,734	6,451,429	102	29 January 1990	1901-2004
Narrogin	516,799	6,355,981	150	29 January 1982	1885-2008
Northam	467,631	6,498,207	126	9 March 1934	1877-2007
Pemberton	412,115	6,187,763	90	17 November 1984	1941-2008
Perth Jandakot Aero	386,773	6,447,837	173	9 February 1992	1972-2007
Perth-Kalamunda	411,191	6,461,383	125	29 July 1987	1908-1993
Perth A.P.	403,237	6,467,131	132	9 February 1992	1944-2007
Perth Reg. Off.	393,182	6,463,916	121	9 February 1992	1877-1992
Perth Subiaco Tre. Plant	385,655	6,463,347	98	29 July 1987	1967-2007
Perth- Nedlands UWA	388,527	6,460,052	83	17 February 1955	1940-1970
Perth-Fremantle	382,947	6,452,229	90	29 July 1987	1852-1989
Perth Kwinana BP Refinery	383,164	6,433,383	212	9 February 1992	1955-2008
Perth Medina Res. Station	387,863	6,434,545	230	9 February 1992	1983-2008
Pingelly	507,803	6,400,401	107	29 January 1990	1891-2008
Port Hedland A.P.	670,297	7,746,445	387	27 January 1967	1942-2008
Port Hedland P.O.	664,357	7,752,990	283	2 March 1941	1898-1948
Ravensthorpe	782,702	6,280,207	113	5 January 2008	1907-2008
Roebourne	515,154	7,702,550	213	31 January 1946	1887-2008
Rottnest Island	358,531	6,457,585	158	9 February 1992	1881-2008
Southern Cross	721,744	6,542,349	84	4 February 1918	1889-2007
Wagin	531,679	6,314,558	142	17 February 1955	1891-2007
Wandering Comparison	469,587	6,383,973	138	17 February 1955	1888-2003
Wongan Hills Res. St.	473,866	6,587,997	86	22 January, 2000	1937-2000
Yalgoo	468,910	6,865,170	142	17 February 1970	1898-2008
York	477,779	6,470,645	74	13 January 2006	1996-2008
York P.O.	477,122	6,472,428	147	9 March 1946	1877-1996

APPENDIX 6-1 BMPS INFORMATION STORED IN EXCEL WORKBOOK

A	B	C	D	E	F	G	H
ID	BMP	Categories	Criteria	Description	References	Link	
1	Riparian Buffer	Purpose	Sediments	Riparian buffers help improve water quality by filtering or retaining sediment particles and chemicals, such as nutrients and toxics, preventing them from reaching the waterways. Roots of buffer vegetation create breaches in the soil, promoting rainwater infiltration and groundwater recharge while moderating			
2	Riparian Buffer	Purpose	Nitrogen	Reduces Nitrogen; Effective at immobilizing, storing, and transforming chemical inputs (fertilizers, pesticides, etc.) from uplands.			
3	Riparian Buffer	Purpose	Phosphorus	Reduces Phosphorus; A riparian buffer reduces the effects of upland sources of pollution by trapping, filtering, and converting sediments, nutrients, and other chemicals.			
4	Riparian Buffer	Purpose	Pollutants	Reduces discharge of pollutants from storm drainage systems to the Maximum Extent Practicable (MEP).			
536	In-stream Stuctu	Issues	Suitabililty	Instream structures may not be appropriate in channels with unstable banks.	http://shelbycountyswcd.org/PDF%20files/Open%20Stream%2		
537	In-stream Stuctu	Issues	Blocks runoff	The structures should not be so high as to block flood flows.	http://shelbycountyswcd.org/PDF%20files/Open%20Stream%2		
538	In-stream Stuctu	Issues	Trees	Felled trees in streams should be sufficiently anchored to avoid creating flow-im	http://shelbycountyswcd.org/PDF%20files/Open%20Stream%2		
539	In-stream Stuctu	Current Usage		On the Serpentine River and the associated drainage system fencing and reveg	http://www.peel-harvey.org.au/content/our_projects/p2_2_msr		
540	In-stream Stuctu	Current Usage		On the Murray River on the Ravenswood Sanctuary reach, there has been two	http://www.peel-harvey.org.au/content/our_projects/p2_2_msr		

APPENDIX 6-2 INFORMATION ON SILT TRAP OR IRRIGATION MANAGEMENT IN THE 'BMP TOOLBOX'



ID	BMP	Categories	Criteria	Description		Link
320	Silt Trap	Purpose	Management	Silt traps are basically a holding area which has considerably more capacity than the inflow into it. Traps cut down water velocity and allows silt to settle out. This will invariably also result in pollutants falling out as well. In some instances this treatment could result in significant reduction in pollutants entering the	Report on Drainage Reform Options for	
321	Silt Trap	Purpose	Management	To reduce the amount of silt leaving farmers fields enough so that the amount of silt entering the waterways, estuaries and Sea is reduced by 30-50%.	REDUCING SILT IN YOUR IRRIGATION	
322	Silt Trap	Purpose	Conservation	A field border is a band or strip of perennial vegetation established on the edge of a cropland field. A field border reduces sheet, rill, and gully erosion at the edge of fields; protects water quality by trapping sediment, chemical and other pollutants; provides a turning area for farm equipment; and provides	http://www.dep.state.pa.us/river/Nutrient%20	
323	Silt Trap	Purpose	Management	Keep trees, shrubs, perennial grasses or legumes along steep slopes, drainage	http://www.ecy.wa.gov/programs/wq/wqguide/	
324	Silt Trap	Purpose	Filter Strip	A filter strip is an area of grass or other permanent vegetation used to reduce sediment, organics, nutrients, pesticides, and other contaminants from runoff and to maintain or improve water quality. Filter strips intercept undesirable contaminates from runoff before they enter a waterbody. They provide a buffer	http://www.nrcs.usda.gov/TECHNICAL/ECS/a	
325	Silt Trap	Purpose	Filter Strip	Filter strips slow the velocity of water, allowing the settling out of suspended soil particles, infiltration of runoff and soluble pollutants, adsorption of pollutants on soil and plant surfaces, and uptake of soluble pollutants by plants.	http://www.nrcs.usda.gov/TECHNICAL/ECS/a	
326	Silt Trap	Purpose	Grassed Waterw	Grassed waterways are strips of grass and other non-woody perennial vegetation that are established in agricultural fields where water concentrates or flows off of the field. Grassed waterways established to prevent gully erosion and trap contaminants and field sediments potentially provide many benefits to	http://efotg.nrcs.usda.gov/references/public/I	
327	Silt Trap	Scale	Farm	Where used • At the lower edge of crop fields or in conjunction with other conservation practices. • On fields along streams, ponds, lakes, and drainageways.	http://www.nrcs.usda.gov/TECHNICAL/ECS/a	
328	Silt Trap	Applications	Sedimentation /(	To reduce the need to de-silt the drains, which reduces maintenance costs.		
329	Silt Trap	Applications	Nutrients	It reduces nutrient levels, which restricts weed growth.		

APPENDIX 6-3 INFORMATION ON NITROGEN OR ALGAL BLOOM IN THE 'BMP TOOLBOX'

ID	BMP	Categories	Criteria	Description	References	Link	
2	Riparian Buffer	Purpose	Nitrogen	Reduces Nitrogen; Effective at immobilizing, storing, and transforming chemical inputs (fertilizers, pesticides, etc.) from uplands.			
13	Riparian Buffer	Effectiveness	Nitrogen	The type, size and effectiveness of riparian buffers vary based on the location, environmental management needs and landowner needs. Riparian forest buffers can reduce N by 40 - 100%, Grass buffers can reduce N by 10 - 60% (improved with vegetation). In experimental studies of grass and combined			
47	Waterway Restoration	Purpose	Nitrogen	Adequately restored drains take excess water from these low-lying areas to the coast either through adjacent estuarine or ocean outlets. In the lower coastal plain controlled drainage is the most effective BMP for reducing nitrogen losses into streams and ditches.	http://www.neuse.ncsu.edu/Ag%20620.pdf		
83	Waterway Restoration	Monitoring requirements	Algal blooms	Algal blooms from increased nutrient levels in the waters. Moderately high algal productivity will generally exist with TP in the range of 20 to 50 µg/L (Gilliom, (1984) and Simpson and Reckhow (1979)). TN to TP ratios should be maintained above 10:1 to prevent blue green algae.	http://www.ecy.wa.gov/pubs/0410033.pdf		
290	Control Stock Access	Effectiveness	Nitrogen	It reduces nutrient levels, which restricts weed growth. Nitrogen 60%			
408	Effluent Manageme nt	Monitoring requirements	Algal blooms	Algal blooms from increased nutrient levels in the waters. Moderately high alga	http://www.ecy		
430	Fertilizer Manageme nt	Applications	Algal blooms	Both N and P are present in natural waters. Where significant N or P are added,	algal blooms		stems, cyno ria (blue-gre
434	Fertilizer Manageme nt	Applications	Nitrogen	Leaching of N frequently occurs via high N concentrations from grazing animal u	http://www.uid	nl	
437	Fertilizer Manageme nt	Effectiveness	Nitrogen	Livestock waste management system will give efficiency of Phosphorus 75%, Nitrogen 75%			
445	Fertilizer Manageme nt	Technical Consideration	Nitrogen	N movement to surface waters via artificial drainage-drainage lines are a direct pipeline from the root zone to the river. Fenelon & Moore (1998) state that much more nitrate enter river from subsurface drains than from base flow (Indiana)			